Process Improvement in Phlebotomy

Yunqu Huang

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Goodman School of Business

Brock University, St. Catharines, Ontario

Abstract

This study has two main objectives. First, the phlebotomy process at the St. Catharines Site of the Niagara Health System is investigated, which starts when an order for a blood test is placed, and ends when the specimen arrives at the lab. The performance measurement is the flow time of the process, which reflects concerns and interests of both the hospital and the patients. Three popular operational methodologies are applied to reduce the flow time and improve the process: DMAIC from Six Sigma, lean principles and simulation modeling. Potential suggestions are provided for the St. Catharines Site, which could result in an average of seven minutes reduction in the flow time. The second objective addresses the fact that these three methodologies have not been combined before in a process improvement effort. A structured framework combining them is developed to benefit future study of phlebotomy and other hospital processes.

Keywords: *phlebotomy, process improvement, six sigma, lean, simulation*

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1. Introduction

The phlebotomy process starts when a decision is made to do a blood test and ends when the specimen arrives at the lab. Many people around the world undergo this process every day (Valenstein, Raab & Walsh 2006). The purpose could be transfusion, disease testing or an annual physical exam. There are multiple steps and different staff members, who may intervene during the process (Lima-Oliveira et al., 2013). Moreover, nearly 70% of diagnoses depend on the results of laboratory tests that occur based on the phlebotomy process (Granata 2011). The quality and timeliness of these results can be significantly influenced by the phlebotomy process. The slightest mistake or delay may have serious consequences such as disease aggravation or shock. Thus, referring to the critical role of the phlebotomy process, this study focuses on the phlebotomy process and uses three methodologies to assess and improve it.

One popular issue in previous literature is the error rate within the process. As discussed in Wagar et al. (2008) and Grimm et al. (2010), human errors, including patient misidentification, mislabeling and missing specimens, are the most serious issues in the phlebotomy process. Even though previous studies have reduced the error rate to a lower level (Wagar et al., 2008 & Grimm et al., 2010), it is still an essential factor that both hospital managers and patients are concerned about (Morrison et al., 2010; Trask & Tournas 2012).

Besides the error rate, timeliness (long collection time, long waiting time, or both) is a prevalent issue in phlebotomy processes across the world. According to Melanson et al. (2009), the patient waiting time before improvement was 21 minutes, but after using lean thinking, they reduced it to 5 minutes on average. Lean thinking was used to reduce some unnecessary steps and modify the process. Morrison et al. (2011) studied the inpatient phlebotomy in the same hospital and improved the inpatient phlebotomy collections by moving the median time of morning collections earlier. They adjusted the staff schedule to match the demand of blood test orders.

This study examines the phlebotomy process in the emergency department of the St. Catharines Site of the Niagara Health System (NHS) in Canada. Initially, the plan was to improve the process by reducing the error rate as well as improving its efficiency. However, the hospital did not provide any data on errors, and no errors occurred during the observation period. Therefore, this study will only focus on improving the process efficiency.

To evaluate the process efficiency, there are a number of different aspects to consider, for example, waiting time and collection time, as mentioned above in the two previous studies. However, in this study, we decided to use flow time of the entire phlebotomy process as the performance measurement. From the hospital's historical records, long flow time is the most obvious problem in the process. Moreover, the flow time reflects the concerns of both hospital and patients. From the hospital's perspective, a long flow time could decrease the productivity of hospital resources, reducing the number of patients that can be serviced in an ED room. From the patients' point of view, the waiting time will increase and patient length of stay in the ED will be extended if flow times are long, which could have a negative effect on the patient's satisfaction. In addition, something of concern to both patients and providers is that long flow times will delay the medical diagnosis, possibly delaying urgent treatment needed by the patient.

To the best of our knowledge, we could not find any evidence that flow time has ever been studied for a phlebotomy process. The flow time in this study is defined to start at the time the blood test is ordered and end when the specimen arrives at the lab. This time is called turnaround in the studied hospital and it is the major performance measurement the hospital wants to improve on. It should be noted that in order to get the lab test results back to the doctor or nurse that ordered them, there is another important component – that of the testing time in the lab. However, the St Catharines Site of the NHS (Niagara Health System) is not currently interested in studying this portion of the process because it is being managed well, has been improving every month, and has almost reached its targets for processing times. Therefore this thesis will focus only on the phlebotomy portion of the process.

With respect to process improvement, some prevailing methods, such as Lean Thinking, have been used for decades. Lean refers to a philosophy that offers a tactic to define the value, streamline the valuable activities in a proper manner, perform these activities constantly and just in time, and lastly make them more and more effective (Womack & Jones 2003). Morrison et al. (2011) and Melanson et al. (2009) applied lean thinking to advance the phlebotomy process. The former reduced the number of delayed collections by 80% while the latter made the patient waiting time decrease by 76%.

Another popular method, simulation modelling, applies to process improvement extensively in hospitals. Simulation means a set of techniques and applications to imitate real-world behaviors, and is typically used in computer softwares (Kelton, Sadowski & Swets 2010). Rohleder, Bischak & Baskin (2007) and Groothuis et al. (2002) set up simulation models of outpatient phlebotomy departments (centers); the models were used to investigate the influences of different facilities locations and layouts.

The third method is Six Sigma. According to Harry and Schroeder (2000), Six Sigma provides a structural approach that allows companies to intervene and control their everyday business activities by designing and monitoring products or services. It helps to improve processes in ways that minimize variation and the use of resources while increasing the product or service quality. In the Kyungpook National University Hospital, Kim, Song and Lee (2009) performed a Six Sigma procedure (Define, Measure, Analyze, Improve and Control, DMAIC) in its outpatient phlebotomy section that successfully reduced the patient waiting time. This paper is written in Korean, and although an English abstract was accessed, it is not possible to study their work.

In addition to these methodologies, a high technology—barcode system has been widely installed in phlebotomy processes as well. This system usually includes a barcode patient wristband, barcode labels and a machine that scans the barcodes (Morrison et al., 2010). Snyder et al. (2012) and Trask & Tournas (2012) declared that the error rate of the phlebotomy process decreased dramatically with the help of the barcode system.

Based on the previous literature, there is no evidence written in English showing a comprehensive quality improvement method applied to phlebotomy processes. Therefore, this study will analyze and advance the phlebotomy process by providing such a method that combines three methodologies—lean, Six Sigma and simulation.

It is fairly common for researchers to use lean and Six Sigma together, but it is rare to combine simulation with them. The most important role of simulation in this study is to evaluate the outcomes of the phlebotomy process accounting for its variability and complexity, including different environmental conditions. For example, the order interval time and the service time are unpredictable and the service times of each process step are impacted by other duties and interruptions the hospital staff experience, which causes the process complexity. Simulation is also good at dealing with the process variability, one aspect of which is analysis of the queues that develop within the process. Without a simulation, it is difficult to predict where waiting could occur when the system is changed and what its influence is on the flow time. In addition, this study generates quite a few suggestions for improvement based on lean and Six Sigma thinking. Simulation helps to demonstrate the impact that these proposed suggestions would have on the process before they are implemented.

Moreover, we tested an experimental factor—the demand level. As the patient number in the St. Catharines Site increases in the future, the number of blood test orders could increase as well. By using a simulation, we could predict how the process would change as demand increases in the future.

Six Sigma's classic five-step DMAIC procedure is used as our major framework in this study. Within the DMAIC framework, we integrate five lean principles and the simulation modeling steps. Detailed steps and their corresponding outcomes are demonstrated with various tools used in the framework.

1.1 The Phlebotomy Process at the St. Catharines Site of the NHS

The Niagara Health System (NHS) is Ontario's largest multi-site hospital system, consisting of six sites. It serves 434,000 residents through the 12 municipalities comprising the Regional Municipality of Niagara. A variety of inpatient and outpatient clinics/services, including Acute Care, Surgical Care, Emergency and Urgent Care, Kidney Care, Complex Care, Mental Health and Addiction, Long Term Care and Cancer Care, are offered at the six sites. The NHS has a yearly operational budget of approximately $468 million, running a group of operatives of 4,195 employees, 621 physicians and 1,100 volunteers (NHS 2013B, based on fiscal 2013-14).

The new St. Catharines Site of the NHS, which opened on March 24, 2013 and replaced the St. Catharines General and Ontario Street sites, is the community hospital for residents of St. Catharines, Thorold, Niagara-on-the-Lake and surrounding communities. It has a combined Urgent Care and Emergency Department and the Laboratory Medicine Program offers 24-hour diagnostic testing availability for treating emergency and routine hospital patients. (NHS 2013B)

This research will focus on the phlebotomy process in the Emergency Department (ED), which includes Urgent Care (UC) and Emergency Room (ER) patients. The UC patients are the patients that need medical attention but are not in a life-threatening state, while the ER patients are very sick patients that have recently arrived (their injuries or conditions are life-threatening).The phlebotomy process, which starts when a blood test is ordered and ends when the blood specimens arrive at the lab, requires multiple steps (e.g., entering information, printing out labels, collecting blood and labeling specimen) to complete. Steps in the phlebotomy process are different depending on the types of patient and also varies with different service providers.

Currently, the average flow time of phlebotomy at the St. Catharines Site is more than 30 minutes. It concerns the lab manager, who thinks that it is unreasonably long and can be reduced. Moreover, there are many interruptions and variations in the process. During a phlebotomy process, an ER nurse, who needs to take care of four patients at the same

time, may be interrupted by many other tasks (e.g., another patient needs immediate attention). In addition, the blood test order interval time is unpredictable. It varies through a day, for example, there could be 2 hours or just a few seconds between two orders. The interruptions and delays are waste within the process, which will be suitable to demonstrate the benefits of using lean principles. Secondly, the process variability and complexity are the reasons why it is also suitable to demonstrate the usage of Six Sigma and simulation.

Thus, this thesis will study and analyze the process by combining the three methodologies (lean, Six Sigma, simulation). Methods and tools from all three will be combined to form a structured framework - which will be discussed later. Combining methodologies can allow the pursuit of different research questions and provide unique insights that are not possible with a single one.

Individually, the merits of applying lean, Six Sigma or simulation can be briefly summarized as follow: first, the process team could reap from lean principles by identifying and eliminating wastes, for example, the interruptions in the phlebotomy process (Womack & Jones 2003). As a result, the flow time will be reduced. Six Sigma is a data-driven methodology for process organization and problem solving (Evans & Lindsay 2003). Under the procedures of Six Sigma, the phlebotomy process can achieve continuous quality improvement in a patient care process, which could be improved and controlled accordingly. Third, owing to the stochastic and intricate nature of the phlebotomy process, simulation provides a vibrant platform to capture the dynamic and complicated features and its development, as well as predict the consequences of potential improvement (Kelton et al., 2010).

Hence, the goals of this study are first to provide insights that can assist in the understanding and improvement of the phlebotomy process – increasing its efficiency (reducing the flow time). Secondly, it is to provide a framework that combines lean, Six Sigma and simulation to guide future efforts. Specifically, the ED phlebotomy process in the St. Catharines Site will be studied by using the combined framework to guide the

research efforts and provide suggestions to the hospital. Based on the findings and experiments, the framework will be modified and generalized for broader areas of health care process improvement. The main performance indicator will be the flow time, which has rarely been studied in phlebotomy processes before. This study contributes to the literature by filling the gap that exists because no systematical process improvement methods have been used in phlebotomy processes, as well as by adding a new integration of methodologies to evaluate them.

The idea of using a combination of methodologies was generated by reviewing the literature that uses combined methodologies in health care process improvement. This is explained, along with practical details of phlebotomy processes and lean, Six Sigma and simulation, in the next section.

2. Literature Review

2.1 Introduction

This chapter will review the related literature in four different focus areas. First, it will review phlebotomy process literature. The three aforementioned methodologies to be used in this research have been used in health care improvement projects in the past, but have rarely been combined, or been used in the study of phlebotomy, for that matter. Thus, the second area of review (section 2.4) focuses on the application of lean and Six Sigma in various areas of health care. The third part covers the combination of lean and simulation in health care. The fourth section considers the use of simulation and Six Sigma in health care processes. The final part summarizes the current circumstance in phlebotomy processes and identifies how lean, Six Sigma and simulation can be integrated to improve it.

2.2 The Phlebotomy Process

For many hospitals, laboratories are an intensive research area and a large portion of diagnosis-based information is sourced from them. Analysis within laboratories has been greatly improved because of certain automations and information techniques, but the outside phlebotomy process, mostly handled by humans, is little-studied and still problem-prone. The following sections show the few investigations that have been done within the phlebotomy process.

2.2.1 Error Rate in Phlebotomy Processes

Reducing the error rate of the phlebotomy process is often a major goal of lab managers. In 2008, a survey investigating 147 clinical laboratories in the US showed that mislabelings were detected at a rate of 0.92 per 1000 labels through 3.3 million specimen labels (Wagar et al., 2008). Two years later, Grimm et al. (2010) claimed that the aggregate labelling error rate was 1.12% in 122 US clinical laboratories. Even though the error rate has been reduced to a lower level, it is still far from the ultimate goal of zero.

The three most critical human errors – all directly related to patient identification – are specimen/requisition mismatch, unlabeled specimens and mislabeled specimens. In order to reduce these mistakes, the University of California, Los Angeles (UCLA) Clinical Laboratories set up three patient safety interventions: a) reorganization of phlebotomy services, b) implementation of an electronic event reporting system and c) installation of an automated specimen processing system. The numbers of all three errors underwent a significant decrease after the interventions. (Wagar et al., 2006)

Correct specimen identification (e.g., blood type) and labeling are also prerequisites of transfusion safety. The Boston University Medical Center had a mislabeling error rate of 0.5% in their transfusion service. The researchers classified the mislabeling into two catagories: major mislabeling error and minor mislabeling error, and focused on the major ones because of the severity and frequency (47% of all errors). The major mislabeling errors were unlabeled specimen, mismatched specimen/requisition, ABO/Rh result on current specimen not matching historical record on file. Then, the researchers organized a quality improvement intervention, providing feedback to the staff members so that they could learn about their errors and adjust for them right away. After the intervention, the major mislabeling error out of the total mislabeling error fell from 47% to 14%. (Quillen & Murphy, 2006)

The above interventions of preventing errors do show improvements for a short period, but it may not be able to continue in a long run without control. Activities of staff member and process flow might go back to the previous state when the interventions are over (Harry & Schroeder 2000). In addition, most of these interventions only focused on reducing error rates and did not consider other essential performance measurements (e.g., process efficiency). Therefore, there is opportunity to use a structured framework of combined methodologies which can be used to address both process error and process efficiency. This study is going to provide such a framework to improve the phlebotomy process by increasing its efficiency (reducing flow time).

2.2.2 Barcode Systems in Phlebotomy Processes

By no means do nurses or phlebotomists want to put patients at risk or cause harm by making mistakes. However, they require a good system and a well-designed process to ensure patient safety: easy and correct patient identification, and keeping track of which specimens, medications and procedures are for which patient. (Granata 2011). Some hospitals have addressed this by installing a barcode system for Electronic Positive Patient Identification (EPPID). This system helps to reduce misidentification and mislabeling of nurses or phlebotomists. A typical barcode system contains bar coded patient wristbands, handheld computers, bar code scanners, and portable printers to generate labels (Morrison et al., 2010). The barcode patient wristband can be scanned and proper specimen labels can be printed at the bedside just after patient identification.

Hospitals that installed a barcode system in their phlebotomy process have yielded a positive and significant outcome in error reduction. In the inpatient phlebotomy service of Brigham and Women's Hospital, Boston, MA, for instance, the mislabeling rate fell from 5.45 in 10,000 to 3.2 in 10,000 (P = .0013). An assessed 108 labelling errors were avoided by the system in one year (Morrison et al., 2010). Norman Regional Health System in Norman, Oklahoma achieved 100% proper labeling in the first two days of the implementation of the barcode system. Howard County General Hospital in Columbia, Maryland used a barcode system to reach zero mislabeling rate in all areas. (Trask & Tournas 2012) Thanks to the barcode system, nine hospitals in Pennsylvania achieved a 37% decrease in errors after implementing a project that analyzed labeling errors and designed devise solutions (PA hospital, 2011).

A study of Snyder et al. (2012) systematically reviewed the effectiveness of barcoding practices in 17 relevant studies. They evaluated the effectiveness by assessing their patient specimen and laboratory testing identification error rate. All 17 studies preferred the barcode system. Based on this, the authors recommended the barcode system as a "best practice", and concluded that barcoding was effective in preventing identification errors in various hospital settings.

Installing the Barcoding System is a robust and superior approach that helps to eliminate misidentification and mislabeling. However, within the phlebotomy process, the mistakes are not the only issue. Timeliness and efficiency are equally important. To address these, some quality improvement principles and tools, such as lean, Six Sigma and simulation can be employed. These will not only advance the process by eliminating errors, but also improve it by accelerating the process flow.

2.2.3 Lean in Phlebotomy Processes

Generally, a phlebotomy process, which contains a set of steps (e.g., entering information, printing out labels), looks simple and short. However, the process effectiveness and efficiency are not easy to control. For example, a long flow time may have a great influence on medical outcomes. For institutions with a phlebotomy service, the timely availability of test results is likely to rely on the timeliness of blood collections, as discussed in Morrison et al. (2011). Lean can prove to be particularly useful in this case.

The Brigham and Women's Hospital, a 777-bed academic medical center, applied lean principles across the inpatient phlebotomy service aiming to optimize their staffing model and improve service without using additional resources. By relocating the staff members and decreasing the number of staff members per shift, the median time of morning collections finished 17 minutes earlier than before the alteration. Statistically speaking, the rate of collection that were delayed (called "postponed collections") decreased 80% from 10.6 per 30 days to 2.2 per 30 days. (Morrison et al., 2011)

Earlier in the same hospital, Melanson et al. (2009) used lean principles to remove unneeded steps and extraneous motions in the phlebotomy process. They aimed to reduce the patient waiting time, proficiently handle the workload during peak times, and eventually improve the patient satisfaction. Non-value added steps in the phlebotomy process (e.g., double checking the specimen before sending) were eliminated or adjusted. The process control charts showed that after the Kaizen Event (lean event), the average patient waiting times were reduced to 5 minutes from 21 minutes, and 90% of patients

had their blood samples started within 10 minutes of their arrival at the phlebotomy station.

However, we believe this research would have made even more improvements if more quality improvement tools were applied. For instance, Melanson et al. (2009) used process control charts, one of the Six Sigma tools, to indicate the tendency of patient wait time after the Kaizen event. If another Six Sigma tool—cause and effect diagram—was used, they would be able to identify the root cause as well as the effect of the variation. By creating a cause and effect diagram, the team members would clearly recognize the causes and effects of the process performance. They would also be able to solve the problem in connection with its root cause. Furthermore, if simulation was combined with lean principles, it would be possible to better assess the waiting time (performance measurement) and reallocate the resources to increase the utilization.

2.2.4 Simulation Modelling in Phlebotomy Processes

Like many other health care service organizations in the world, Calgary Laboratory Services (CLS) in Alberta, Canada faced increasing demand and limited resources. This required the CLS to relocate its "resource"—phlebotomy and specimen centers (PSCs) – within the network to increase efficiency. They utilized simulation modelling to relocate the facilities. Their objective was to reduce the average waiting time and its variability, and to eventually improve the patient experience. The simulation model results suggested that CLS centralize its PSCs (from 25 sites to 18 sites) to increase resource utilization and decrease demand variability. This initiative would allow 80% of patients to wait less than 20 minutes. (Rohleder et al., 2007)

Another study by Groothuis et al. (2002) also applied simulation modelling to relocate a hospital outpatient phlebotomy department. They used the patient turnaround time as a performance measurement to select the proper facility layouts and phlebotomy procedures (e.g., using a pneumatic tube to transport specimens to the lab). Current and future simulation models were analyzed and compared for different scenarios. In the best scenario, the average patient turnaround time decreased from 12 minutes to 8 minutes,

ensuring that the current personnel could handle any increased patient volume even in the peak time (Groothuis et al., 2002).

The difference between Rohleder et al. (2007) and Groothuis et al. (2002) is their investigative targets. The former focused on the number of phlebotomy centers in a particular network, while the latter investigated the actual layout within one specific phlebotomy department. Yet, they both took full advantage of simulation modelling and used its ability to capture the system dynamics in the health care context in order to increase phlebotomy efficiency.

However, if the authors merged simulation with lean and Six Sigma concepts for the phlebotomy process, the performance (e.g., waiting time, flow time) may be further improved, which will be addressed in this study. For example, a value stream map in lean can indicate the redundant processes and a spaghetti diagram might be used to identify the unnecessary motion within the phlebotomy Department. This possibility is addressed in this study.

2.2.5 Other Efforts in Phlebotomy Processes

Mannion and Nadder (2007) conducted research to investigate the effectiveness of three alternative structural arrangements for inpatient phlebotomy—centralized, hybrid and decentralized. The centralized design meant that the laboratory managed and delivered all the phlebotomy services, whereas in the case of decentralized design, nurses and nurse extenders (e.g., patient care assistants) carry out the phlebotomy process. A non-experimental prospective survey was distributed to 31 hospitals with onsite laboratories in the United States. The effectiveness of blood collection processes was measured by the percentage of specimens rejected during the data collection period. Based on the results of analysis of variance and post-hoc comparison (Tukey's HSD), the centralized inpatient phlebotomy configuration was found to be more effective than the decentralized or the hybrid. (Mannion & Nadder 2007)

Moreover, Lima-Oliveira et al. (2012) researched the usage of a guideline—CLSI (Clinical Laboratory Standard Institute) procedures (CLSI/NCCLS H03-A6 - Procedures for the Collection of Diagnostic Blood Specimens by Venipuncture) in training staff to collect diagnostic blood specimens. The results showed that the CLSI procedures could remarkably improve quality since the thirty well-trained phlebotomists completely eliminated non-conformity (Lima-Oliveira et al. 2012).

This study is going to test if the structural arrangement influences the process performance, as did Mannion and Nadder (2007). The options available at the St Catharines Site of NHS are centralized, hybrid and decentralized as well. This is going to provide managers with information necessary to organize their phlebotomy arrangements.

2.2.6 Summary

Although previous work on the phlebotomy process showed good results, some of them lacked systematic improvements or general methods. Thus, this study intends to understand the phlebotomy process and advance the current literature by developing such a process improvement framework—combining three methodologies. The next four sections will provide a comprehensive summary of three general process improvement methods, namely, lean, Six Sigma and simulation, and elaborate on how they have been used together to improve health care outcomes. Since these methods have rarely been used to improve the phlebotomy process, this review incorporates studies that have used these methodologies in other health care processes. This review will give a more wholesome view of the combined effect of different methodologies, which will help in developing designs for improving the phlebotomy process.

2.3 Review of Lean, Six Sigma and Simulation

2.3.1 Lean

Lean thinking is a methodology that “provides a way to specify value, line up value-creating actions in the best sequence, conduct these activities without interruption

whenever someone requests them, and perform them more and more effectively" (Womack & Jones 2003). It is widely believed that lean methodology mostly originated from the Toyota Production System (TPS), invented by a Japanese manufacturing company. Today, it has spread out to every industry, including health care. In lean thinking, seven original wastes were classified: Transport, Inventory, Motion, Waiting, Overproduction, Over Processing and Defects. All of them have specific explanations in the health care context. The value of lean is identifying and eliminating these seven kinds of waste within a process so that products or services can be delivered in a much faster and smoother fashion without interruptions and delays (Womack & Jones 2003).

In terms of the health care industry, the seven wastes in health care (NHSI 2008) are defined below:

1) **Transportation.** This refers to any redundant patient or material movement, e.g., patient movement from one ward to another for review, and then to another place for discharge.
2) **Inventory.** This denotes unnecessary materials or patients that are 'stored' in the hospital, e.g., ordering excess materials (tests) because the previous supply is unreliable.
3) **Motion.** This could be needless movements in the workplace relating to layout and arrangement, e.g., having to look for paperwork or equipment that is far from one's workstation.
4) **Waiting.** This refers to a patient or staff waiting, e.g., having to wait in queues for registration.
5) **Overproduction.** This refers to producing more than is required, e.g., doctors requesting referrals or additional/repeat tests more frequently than necessary.
6) **Over Processing.** This denotes using/involving complex equipment or methods to complete simple tasks, e.g., inflexible and compound processing equipment.
7) **Defects.** This represents the non-conformity or errors within the process, e.g., failed discharge and misidentifying patients.

In addition to eliminating waste, a lean event usually follows five central principles: Value, Value Stream Mapping (VSM), Flow, Pull and Perfection. These five principles lead a quality improvement project from problem identification to continuous improvement. To illustrate, Principle 1—Value – requires researchers to define the value of a product or

service from a customer's standpoint. VSM, the second principle, helps to understand the entire process flow and classify the activity types (value added activity, non-value added but necessary activity and non-value added activity) within the process, which identifies problem areas. The third principle—Flow, asks one to rethink and rearrange activities, e.g., reducing batch sizes. The fourth principle, Pull, means that a product or service should not be processed until the customer orders, while Perfection, the fifth principle, indicates that processes need to maintain and improve continuously (Womack & Jones 2003).

2.3.2 Six Sigma

Six Sigma is a professional approach that allows companies to intervene and control their everyday business activities by fabricating and checking product or service producing processes in fashions that minimize variation and resources while enhancing the product or service quality (Evans & Lindsay 2003). It advances a process by specific methods so that errors or non-conformity never arise in the first place (Harry & Schroeder 2000). Sigma, a letter of Greek alphabet is used to symbolize the standard deviation of a process. A high sigma level is better, as it denotes less output process variation: that is, the process is expected to have no more than 3.4 defects in one million units (Breyfogle, Cupello & Meadows 2001).

In order to meet this criterion, two kinds of typical Six Sigma frameworks—DMAIC and DMADV are applied extensively in process improvement (DMAIC: Define, Measure, Analyze, Improve and Control; DMADV: Define, Measure, Analyze, Design and Verify). DMAIC is to rearrange or adjust a process that already exists while DMADV is for new process design and implementation. In this paper, DMAIC procedures incorporating a set of quality improvement tools are applied to the phlebotomy process. Samples of some potential tools are listed below: Process Maps, Cause-and-Effects Matrix, Measurement Systems Analysis, Process Capability Studies, Failure Modes and Effects Analysis, Multi-Vari Studies, Design of Experiments and Control Plans (Zinkgraf & Snee 1999). Different stages of DMAIC may encompass different tools. For example, the Define stage could use

a Gantt chart to plan the overall project and help the project creation (More information on Six Sigma can be found in Evans & Lindsay, 2003).

2.3.3 Simulation

Simulation refers to the imitation of the behavioral characteristic of a real-world process or system (model) and its constant development. The imitation is usually presented on a computer using a broad collection of methods and applications. Including entities (people, products or service), attributes (characters), variables (numbers), resources (equipment), a set of elements are defined in a simulation model, all of which are formed and bonded by a reliable real-world logic. (Kelton et al., 2010) Discrete Event simulation (DES), a particular simulation that this study focuses on, represents simulation events that change instantaneously at distinct points in time (Robinson et al., 2012).

DES is widely applied in real-world quality improvement, partly due to its ability to capture dynamic developments and partly because it helps people to learn the potential results in advance. Usually, an Input Analyzer fits the empirically collected data (e.g., demand and production time) into a certain distribution that DES uses as an input. Many studies apply DES for decision support to compare different scenarios (alternatives of improvement) or determine the best resource allocation (staff number, schedule, equipment and facility etc.). It gives managers and researchers a handy and flexible platform to manage the process and develop well-grounded reasons for improvement. DES has been quite popular over the last few decades in many health care applications including the phlebotomy process (Rohleder et al., 2007 and Groothuis et al., 2002), ED (Khurma, Bacioiu & Pasek 2008; Setijono, Ashkan & Uday 2010; Pelletier et al., 2011), and outpatient clinic (e.g., Klassen & Yoogalingam 2013 and Uppal et al., 2012). (More information on simulation modelling can be found in Kelton et al., 2010).

2.4 Lean and Six Sigma in Health Care

One of the main outcomes of this study is a combined framework that includes the three methodologies. Since these three have not been combined before, the literature review

will focus on times when two of them have been combined for health care improvement. So, the next three sections summarize instances where this has occurred.

2.4.1 Lean and Six Sigma in the Operating Room

Efficiency in Operating Rooms (ORs) has become a popular area for study and the perception that lean or other operational methodologies can benefit the health care sector is flourishing. It is well known that ORs, where surgeries take place, are responsible for a large portion of hospital revenue (Hospital Finance 2007). Based on this, an essential part of hospital resource and research attention has been focused on OR procedures. Some pervasive issues include the labor-intensive nature of the process, schedule delay and low utilization (Cima et al., 2011 and Does et al., 2009). Therefore, lean and Six Sigma, which are two prevalent quality improvement methods, can offer strategies and procedures to help with these problems. Two applications of lean and Six Sigma in ORs are introduced in the following discussion.

In 2007, Fairbanks used lean and Six Sigma to improve the OR throughputs in a southwestern Vermont medical center. He applied DMAIC procedures of Six Sigma and combined lean thinking with the procedures. Each step of his work is summarized below.

First of all, it was the Define component — problem identification. Problems of surgeon or patient dissatisfaction were identified from a survey of surgical and nursing staff members. A Pareto chart of these problems within the process was created, and the result showed that *case delay* was the major problem that gained more than 70% responses. The second place was occupied by *excess paperwork*, which got 9.1%, followed by *other*, *room unstocked*, *IV start,* and *TAT (Turn-around time) exceeded 30 minutes*, which accounted for 5.5%, 4.5%, 3.6% and 3.6% of the responses, respectively. Any effort to improve a system initially should be focused on solving the most frequent causes of the problem. A fishbone diagram of dissatisfaction was also generated to sort out and present the causes and effects. (Fairbanks 2007)

Then, the author constructed a distinct process map including five parts: supplier, inputs, process, outputs and customers (SIPOC). The supplier offered necessary inputs for the process to occur. The outputs of the process helped or met the customers' needs and expectations. During the process mapping, five time spans were decided as measurement: the time for a patient to get ready for surgery, the time for an OR to be set up, the time from a patient being ready to enter the OR, the time for induction of anesthesia or for emergence from anesthesia and the time for room teardown and cleanup. (Fairbanks 2007)

Next was the Measure stage, which created a process capability graph that helped the researchers identify a flaw and a potential improvement within the process. Patient holding time, which proved to have a significant relationship with on-time start in the next stage, showed high variation in the process capability graph. 40.38% of cases took longer than 10 minutes in holding rooms, which, when translated to Defects Per Million Opportunities (DPMO) was 403,846 – far below the Six Sigma target of no more than 3.4 DPMO. It was persuasive statistical evidence for the staff members to realize that the holding time issue had ample room for improvement. (Fairbanks 2007)

The third step in implementing Six Sigma was Analyze, which used statistical tools (e.g., regression analysis) to discover the causal relationships in the process. Fairbanks (2007), formulated a regression model to analyze the effects of the holding time, surgeon arrival time, and team preparedness for an on-time start. The results showed that all three factors had statistically significant relationships with on-time start. This facilitated and supported the next procedure of Six Sigma—Improvement.

In addition to the aforementioned issues, the author found that the structural design (layout) of the hospital facility was arranged in a way that led to a physical waste—transportation. This was identified using the concept of the seven wastes in lean philosophy. For instance, the ambulatory care admission and discharge areas should be located on the same floor as the OR and post anesthesia care unit (PACU). (Fairbanks 2007) Even though the facilities location redesign was a lingering and complicated project, it

was important that the hospital managers were aware of it and planned to make improvements.

In the second-to-last stage, Improvement, Fairbanks (2007) recommended that all the first cases of a day be brought to the PACU to stage for nursing, anesthesia, and surgical assessment before surgery. Patients after surgery needed to return to PACU for recovery or discharge. This alteration made the percentage of on-time starts improve dramatically from 12% to 89%. Then, the author carried out a survey among patients to evaluate the changes. The patients, who experienced reduced transportation and waiting times by these changes were very satisfied with all aspects of care provided, though these changes seemed to reduce privacy.

The Control step was the last step of the event. With the help of proper control tools or methods, such as control charts, the previous improvements could be maintained. Fairbank (2007), conducted a control chart of on-time start to show that, after intervention, the start time was under control. Additionally, patient satisfaction improved during the quarter following the implementation of these changes. The overall facilities rating increased 1.2 points, from 93.2 to 94.4. (Fairbanks 2007)

Another article—Cima et al. (2011) also applied both lean and Six Sigma methodologies to improve efficiency across surgical suites. While Fairbanks (2007), used Six Sigma procedures to improve the process, Cima et al. (2011), focused on lean thinking to eliminate the non-value added activities. What's more, the distinction of Cima et al. (2011), was that they investigated the process of all surgical procedures from surgery decision to discharge, instead of studying one of the sub-processes. Therefore, the questions and findings were multifarious:

Based on the authors' investigation, the first problem they identified was the high variation in surgical volume. This was because of the insufficient OR information (e.g., numbers of surgeries planned on the date and the OR). The surgeons required the information to schedule surgeries. To improve the information providing system, all prescheduled cases, estimated case durations, OR use percentage, and surgeon absences

were necessary to be available to the surgeons, who were responsible for making decisions about elective cases. Developing this information list resulted in a 60% and 53% decrease in surgical listing errors for colorectal and gynecologic oncology surgery (two specialties in this study), respectively. (Cima et al., 2011)

Secondly, the authors found that several preoperative processes influenced the OR throughput. Over 2 dozen staff performed the set of processes in the hospital, which led to a variation of the patient evaluation, and then resulted in surgery delay and cancellation. The suggested method to address this problem was to streamline the preoperative processes, by developing preoperative assessment criteria. (Cima et al., 2011)

Furthermore, a value stream map indicated that staggering OR start times was helpful to relieve the pressure of patient-arrival-time variation. Also, the authors used an important performance metric to sort out the high-chance delay cases that could not start on time, and these cases were not recommended to be scheduled as the first case. After adjusting these two problems, the percentage of on-time starts increased from 60% to 92%. (Cima et al., 2011)

Thirdly, parallel processing was proposed to reduce the non-value added time in ORs. Some nonsurgical tasks conducted in the OR between cases were carried out simultaneously with the ongoing case. Goals of the time between cases were set to each specialty and dispensed to each staff. The percentage of meeting targets was also transparent to all of them. (Cima et al., 2011)

Another problem was the waste of redundant patient information collection and documentation. In order to fix that, the information technology programmers in the hospital developed a comprehensive single-source application. This standardized all the terminology and collection across all the electronic applications and encompassed the entire preoperative process. (Cima et al., 2011)

Lastly, an essential element of successful implementation of lean thinking — Perfection – required full staff engagement. Cima et al. (2011), indicated that staff satisfaction could

substantially influence the long-term success of an efficiency initiative. Therefore, a communication group was formed and regular meetings were held with representatives of stakeholders to exchange information. In addition, they clearly set up different expectations in departments and assigned different responsibilities of staff roles. After that, a briefing time was organized twice a day (before and after the OR operating period) to discuss the general issues including specific medical, surgical or anesthetic issues, personnel matters, operative plan, etc.

The improvements of lean and Six Sigma implementation were numerous within these two high-volume specialties. The patient waiting time at the surgical admissions desk of longer than 10 minutes decreased significantly from 42% to 12%. Overall, the OR efficiency and capacity have improved – operating margin per OR increased by 22% (thoracic surgery), 16% (gynecologic surgery) and 50% (general/colorectal surgery). (Cima et al., 2011)

2.4.2 Lean and Six Sigma in Other Departments/Clinics

The Post Anaesthesia Care Unit (PACU), which has a close relationship with ORs, is also a demanding area in hospitals. Kuo et al. (2011) performed a case study in PACU by introducing a Healthcare Lean Six Sigma System (HLS^3). They claimed that this system was not a simple combination of lean and Six Sigma; it bridged the service gaps between health care providers and patients, while balancing out the requirements of health care managers.

In HLS^3, there were four iterative steps: identify, analyze, action and follow-up. Within each stage, general strategies and goals were elaborated. For instance, in the identify stage, the problem and scope, including the quality indicators, purposes and methods to evaluate, were required to be clear to every quality improvement (QI) team member. In the action stage, team members were asked to draw a big picture of problem-solving countermeasures and they were to confirm improvement results by using performance indicators. (Kuo et al., 2011)

As an example, the PACU study on spinal anaesthesia patients identified seven problems (e.g., inefficient layout) that caused them to stay for unnecessarily long periods. Then, the team used observation and discussion to identify their root causes. According to the analytical results, several suggestions such as redesigning the PACU layout and applying radio frequency identification tags were recognized and listed. After that, the authors built a House of Quality to calculate the priorities for implementation. In the follow-up stage, a follow-up plan, which consisted of targets and latter process details, was used to maintain the improvement. After one iteration of HLS^3, the length of stay in the PACU was reduced from 95 to 40 minutes. (Kuo et al., 2011)

In a similar vein, Chiarini (2012) built a typical lean and Six Sigma model (DMAIC) within a pharmacy department in an Italian hospital. After defining the goals and determining the team members, the author created a value stream map of a typical path of an antiblastic drug – this indicated the wastes within the process. For instance, nurses had to walk a long distance to deliver drugs to departments. According to the brainstorming meeting and the cause-effect diagraph analysis, the team members decided to develop a centralized unit, which enabled the reduction of financial costs in the pharmacy department. This was achieved by removing the immobilized capital inside the stockrooms. The total amount saved due to the improvements was around €200,000.

There are other papers that studied lean and Six Sigma and they are ripe with success stories that present attractive financial returns. The University of Iowa Hospital and Clinics increased the net revenue by approximately $750,000 through utilizing lean Six Sigma methodologies (Bahensky, Roe & Bolton 2005). The Park Nicollet Health Services in Minneapolis, Minnesota conducted lean and Six Sigma projects to achieve a $7.5 million profit in a year (Kim et al., 2006).

In 2010, DelliFraine, Langabeer & Nembhard (2010) summarized research (a meta-analysis) that applied lean or Six Sigma in health care. These two methods show promise in assisting hospitals in clinical outcomes, processes of care or financial performances. 177 articles published on lean or Six Sigma from 1999 to 2009 were considered for

abstract review. Only 34 of these met the criteria and reported any outcomes of the lean or Six Sigma approaches; less than one-third of these articles included statistical analyses to test the significant changes in outcomes.

In order to better assess these articles, the authors calculated an 'Evidence Score' of those 34 articles according to Slavin's criteria (Letzel 1995), where a lower score meant stronger evidence. The total average score of the 34 articles was 6.1; those focusing only on lean scored 5.7; those focusing only on Six Sigma had a score of 6.2, and the ones that had both lean and Six Sigma obtained 5.0 (DelliFraine et al., 2010). This indicated that when considering lean or Six Sigma projects, combining the two may produce better results.

Then, based on their analysis of the prior studies, the authors identified some gaps in the literature: they found that only eleven of the studies had statistical analyses to evaluate improvements. Few articles measured financial outcomes and just thirteen articles talked about it, but twelve focused on improving processes and one focused on improving clinical outcomes. Furthermore, only one article had used a non-equivalent control group design to compare alternative improvements. The article, therefore, ended up with some suggestions for future studies: concentrating on one specific project in one area in a hospital, providing additional details to demonstrate statistically significant improvements, and should measure and report more of the cost-effectiveness of lean and Six Sigma tools. (DelliFraine et al., 2010)

After reviewing the literature on the application of lean and Six Sigma to health care process improvement, it can be said that lean and Six Sigma can be adapted and integrated to enhance each other's benefits in the health care process improvement. Using the two together is recommended by many lean and Six Sigma experts, so this study combines lean and Six Sigma in order to get more positive results than using just one of them.

2.5 Lean and Simulation in Health Care

2.5.1 Lean and Simulation in Emergency Departments

The patient volume today in EDs is growing dramatically, while the resources often remain steady. New EDs opening up cannot match the rate of patient growth; and patients often suffer from long waiting times, which can have a negative influence on staff morale as well as patient satisfaction. Besides treating mainly severely-urgent patients, EDs handle multiple comprehensive tasks and need to guarantee the service quality, but, the limited number of staff and scarce resources hinder EDs' normal functioning. These issues are universal across hospitals around the world, and hospital professionals are facing increasing pressure to find methods to solve them.

Learning from their manufacturing industry counterparts, professionals in the health care industry have begun using lean and simulation in EDs for service improvement recently. Lean is applied to eliminate waste, while simulation is utilized to facilitate lean implementations. Three articles, Khurma et al. (2008), Setijono et al. (2010), and Pelletier et al. (2011) that combined lean and simulation together to advance ED performances are reviewed here.

Khurma et al. (2008) discussed how lean and simulation were used to improve patients' experiences over their ED stays. The authors concentrate on the exploration of how to increase the effectiveness of ED operations. A variety of lean tools, such as Cycle Time Analysis, Work Combination Charts, Cause & Effect Matrix and Fish-bone Diagram were utilized to assess ED performance and address problems within the whole process. After that, the authors built simulation models to show that most patients suffered from long and variant waiting time and different staff members had very different utilization levels. As a result, the authors made several recommendations, such as assigning staff members to day and night shifts according to the demand, reconstructing the layout, and revamping visual management (e.g., more signs to lead patients and a visual board for announcements).

Likewise, Setijono et al. (2010) provided a specific report about the research of lean and simulation in the ED of the Sahlgrenska Hospital in Gothenburg (Sweden). Similar to Khurma et al. (2008), simulation modelling was used as a decision-support system in this study. They used it to compare the current stage and future stage of ED processes and then developed suggestions.

The goal of Setijono et al. (2010) was to find the "best" allocated number of surgeons and medical doctors to balance out the demand in the ED. For such a purpose, they took advantage of simulation models by adjusting the number of surgeons and medical doctors to figure out the minimum patient non-value added time, and the total time as well. Applying lean thinking, the authors successfully identified and eliminated most wastes (the non-value added activities) within the ED process with a value stream map. In the end, it was suggested that the ED might further reduce waiting time by having multiple flow streams, which were separately managed by different personnel, such as "the fast track" and "the regular track".

More recently, Pelletier et al. (2011) also applied VSM and built two simulation models representing current and future ED flows in the HealthAlliance Hospital, the largest health care system in Central and Western Massachusetts. Based on the analytical results of VSMs, the authors conducted a summary table to list the problems, root causes and countermeasures. For example, waiting time for triage was identified as a problem; it was because of the process bottleneck at triage. The countermeasure was scheduling two nurses at the triage station. In addition, according to the simulation models, it was found that the ED should add 10 more beds, 3 medical doctors, 2 nurses and 2 technicians to meet the excess demand. Lean principles and tools (e.g., Flow, Pull and 5S) that were used to redesign the process steps and facility layout also helped to enhance the ED effectiveness and efficiency.

2.5.2 Lean and Simulation in Other Departments

It is increasingly recognized that lean and simulation benefit process improvement in departments, clinics, and in entire hospitals. In an outpatient wound clinic in the US,

Uppal et al. (2012), implemented an experimental study aiming to reduce the flow time, eliminate wastes and increase patient throughputs. Analysis was performed on the patient flow in the whole wound center, starting from the registration to the end of diagnosis, which included every specific treatment room and waiting rooms.

Some lean and engineering tools, such as cause and effect diagrams, value stream maps and statistical control charts, were applied to find out the root cause of variation to identify process wastes and to control the flow time. They used a Fishbone diagram (cause and effect diagram) to sort out the causes of the low patient throughput. Thirteen causes (e.g., cancelations, late arrival) in four categories (patient, people, equipment and process) were identified as having negative effect on the throughputs. The value stream maps were created to document all activities and their times. 35.13 out of 71.79 minutes' total time were recognized as patient waiting times, which were waste and had to be eliminated. Two statistical control charts were formed and they indicated that there were significant variations both in the overall flow time and the time patients spent in the treatment room. (Uppal et al., 2012)

Based on these analytical results, the authors came to some findings and suggestions. Initially, the aim was to design a better scheduling rule. Because most of the studied patients were returning patients, their schedule time depended on their wound severity instead of an average time. Then, some duplicate steps in the service process, such as nurses writing reconciliation forms, were eliminated. By drawing a spaghetti diagraph map for nurse movement, the authors discovered the need to rearrange the specific required equipment in each treatment room so that the nurses' moving time would decrease. Furthermore, a simulation model was built to determine the optimal staffing solution. The authors argued that the simulation model, which provided flexibility in making changes to process parameters, could quickly generate various staff schedules for consideration. Seven staff plans were compared. The optimal and the most feasible was the one with 3 primary nurses and 3 float nurses. (Uppal et al., 2012)

Earlier, Sharma et al. (2007) did research similar to Khurma et al. (2008), Setijono et al. (2010), and Pelletier et al. (2011), in two hospitals in Germany. These four articles used simulation as a decision-support tool to predict results of lean improvements. The difference was that Sharma et al. (2007) applied lean to the entire hospital process from the order taken to patient discharge, instead of one specific area.

The major goal of Sharma et al. (2007), was to reduce the long flow time. The average amount of work (cycle time) of the two hospitals was 84.4 minutes; however, it took about 2.6 days (flow time) to accomplish. The authors aimed to reduce this flow time by using lean and simulation to reorganize the process flow and crew size. First of all, they defined values from the customers' angle and found out that patients expected to complete the process without disruptions (e.g., waiting). Then, value stream maps of the service processes were generated for removing the non-value added processes. Applying the automation technique could facilitate and simplify the steps to reduce interruptions and wastes, which eventually comprised the value stream flow. Simulation models of current stage and future stage were built and the authors compared different crew sizes and process orders in order to attain the minimum average flow time. After lean improvements, the average flow time was reduced to 179 minutes (from 2.6 days). This could be achieved with only one person at the reception center and four people as service crews, compared to 3 at reception and 3 as servers before the lean improvements. (Sharma et al., 2007)

In addition, Swick et al. (2012), and Riley et al. (2012) are another two studies that used lean and simulation approaches for health care process flow. The simulation models in Riley et al. (2012), were used to access the cost-effectiveness of platelet transfusion process, while Swick et al. (2012), studied how to use lean and simulation to enhance the role of professional nurses (increase their value added time). Although the above literature is said to have applied lean and simulation together, simulation is seen to be used only in the last part of the experiment and in predicting alternative results. Their combination throughout an entire study is barely seen.

However, in the same year, during a traditional lean event, three roles of simulation, especially Discrete Event simulation (DES), were developed. These roles were denoted as: Simlean Educate, Simlean Facilitate and Simlean Evaluate; and would be illustrated by three different case studies (Robinson et al., 2012). The authors argued that the combination was a robust tool to yield benefits in health care process improvement.

During the Simlean Educate, DES models provided a visible platform for staff members to learn lean principles and get familiar with the dynamic health care environment. A Simlean Educate example of the theatre processes showed that by running the model and presenting the relevant results to staff at the beginning of a lean event, it was possible to easily acquaint participants with the lean knowledge and tell them where the process problem might occur and how lean could help. Furthermore, the Educate models could simplify the actual modelling in the next procedure—Simlean Facilitate. (Robinson et al., 2012)

In the second stage, a value stream map of the target process was presented as a relatively simple DES model, which could help project team members to better understand the dynamics of the as-is processes and explore alternative ideas for the to-be processes. In Royal Bolton Hospital NHS Foundation Trust, the care improvement team could generate valuable ideas of process redesign on the second day of their lean event due to the quickly built Simlean Facilitate models. More importantly in this stage, the key principle was restricting the amount of highly detailed modeling, which helped to build up a model rapidly and allowed team members to discover the potential improvements within processes. (Robinson et al., 2012)

The third stage was Simlean Evaluate, where DES was implemented within a lean event in a traditional fashion—a decision-support tool. It was believed that a verified DES model could test new ideas and create new suggestions. An example of Simlean Evaluate came from a cystic fibrosis clinic, where the authors were able to determine optimal process orders by detail and continuously adjust DES modeling. (Robinson et al., 2012)

As two mutual supportive methodologies, lean provided an exceptional initiative for the continuous process flow while DES gave an attainable platform for the dynamic environment. Their three combined roles – educate, facilitate and evaluate – stood for 'before', 'during' and 'after' a specific lean event, respectively. They demonstrated interactional impact, from both theoretical and empirical perspectives, in the health care sector. Although DES was used as the decision-support tool in most cases, it was rational to say that DES could be propitious to an entire lean project. Implementing the Simleans could provide unexpected spark during the health care improvement. (Robinson et al., 2012)

As discussed before, combining lean and simulation yields positive results in health care process improvement; and simulation modeling not only enhances the lean effect on the process but also facilitates the lean project implementation. Thus, this study integrates simulation throughout the lean/Six Sigma project. A new combined framework in Table 12 shows details of how they are used together in this phlebotomy process study.

2.6 Six Sigma and Simulation in Health Care

A review of the literature regarding the application of Six Sigma and simulation in health care is scarce. There are only two articles merging Six Sigma and simulation in health care compared to more than twenty in manufacturing. The first relevant article used design for Six Sigma (DMADV) procedures to improve health care processes, while the second one created an innovative improvement roadmap that was suited to both DMADV and DMAIC procedures.

In a Jordanian hospital, Mandahawi et al. (2010), provided an example of using design for Six Sigma to design a new triage process for an Emergency Department (ED). In the ED, Length of Stay (LOS) and Waiting Time (WT) were two factors that highly related to the hospital operation and patient satisfaction. Hence, these two factors were chosen to evaluate the ED performance before and after the design for Six Sigma improvement. Assisting in the Measure and Design stages, DES models showed that LOS had a 34% reduction and WT decreased from 33.21 minutes to 12.93 minutes after the triage

process was implemented. This was achieved without additional staff members. Moreover, the WT sigma level was improved from 0.66 to 5.18, and the LOS figure was improved from 0.58 to 3.09 due to the triage process.

Because the triage system was a new service added in the ED, Mandahawi et al. (2010), utilized DMADV, and not DMAIC, to investigate the process flow. DMAIC is a more commonly used methodology for improving an existing process (Fairbank 2007, Chiarini 2012 and Southard et al., 2012); DMADV, on the other hand, usually applies to designing new products or services to meet the customer expectations. Details on the DMADV framework in Mandahawi et al. (2010) are described as follows:

Define: In this phase, a survey was distributed to a sample of random patients. This determined not only the two critical factors, WT and LOS, but also identified the three project goals, which were (i) to reduce the WT and LOS, (ii) to improve the ED processes Six Sigma level, and (iii) to enable the ED staff to treat patients based on their illness rather than arrival time. They also built a project charter that included all the background information, and that could guide their research. The project charter was reviewed several times by the team members before implementation.

Measure: The central part of this phase was to collect relevant data for the calculation of WT and LOS. Two samples of patients from two random months were selected. Based on these samples, the measured mean of WT and LOS were 33.21 minutes and 84.49 minutes, respectively. A simulation model was built of this system.

Analyze: This phase defined the specifications of and addressed the variables affecting the two factors, WT and LOS. According to the interviews and discussions with patients, the specifications of WT and LOS should have been within 20 and 60 minutes, respectively, in order to meet patient expectations. The triage process, the number of physicians, and the number of nurses were considered as the variables influencing WT and LOS.

Design: This stage used the voice of the customer (VOC) to identify critical factors for designing the new process. Quality Function Deployment (QFD) was the tool that helped to transform the qualitative data into measurable attributes. Consistent with the results

in the Define phase, the QFD showed that WT and LOS should be the critical factors, because reducing WT and LOS were considered the greatest priority by the patients. What's more, the triage process also got the highest score, indicating that it was the most influential variable for achieving patient satisfaction. A modified DES model with a new triage process was created that showed that WT and LOS had undergone 61% and 34% improvement, respectively, compared with the base line data from the Measure phase.

Verify: In this phase, the authors verified the improved DES models by keeping track of patients, physicians and nurses. Reviewing the model code also confirmed the correct general logic of the model. Moreover, a t-test comparing the actual and estimate mean patients' throughput showed that the model was accurately validated with a p-value of 0.57.

Likewise, Celano et al. (2010), introduced a theoretical framework that integrated Six Sigma procedures with DES. In a public hospital in southern Italy, the authors used Six Sigma and simulation to analyze the flow of emergency patients affected by vertigo symptoms illness. They created a new roadmap combining DES and Six Sigma procedures (DMAIC-DMADV) in order to eliminate unnecessary patient examinations and to reduce the time and cost (see Figure 1).

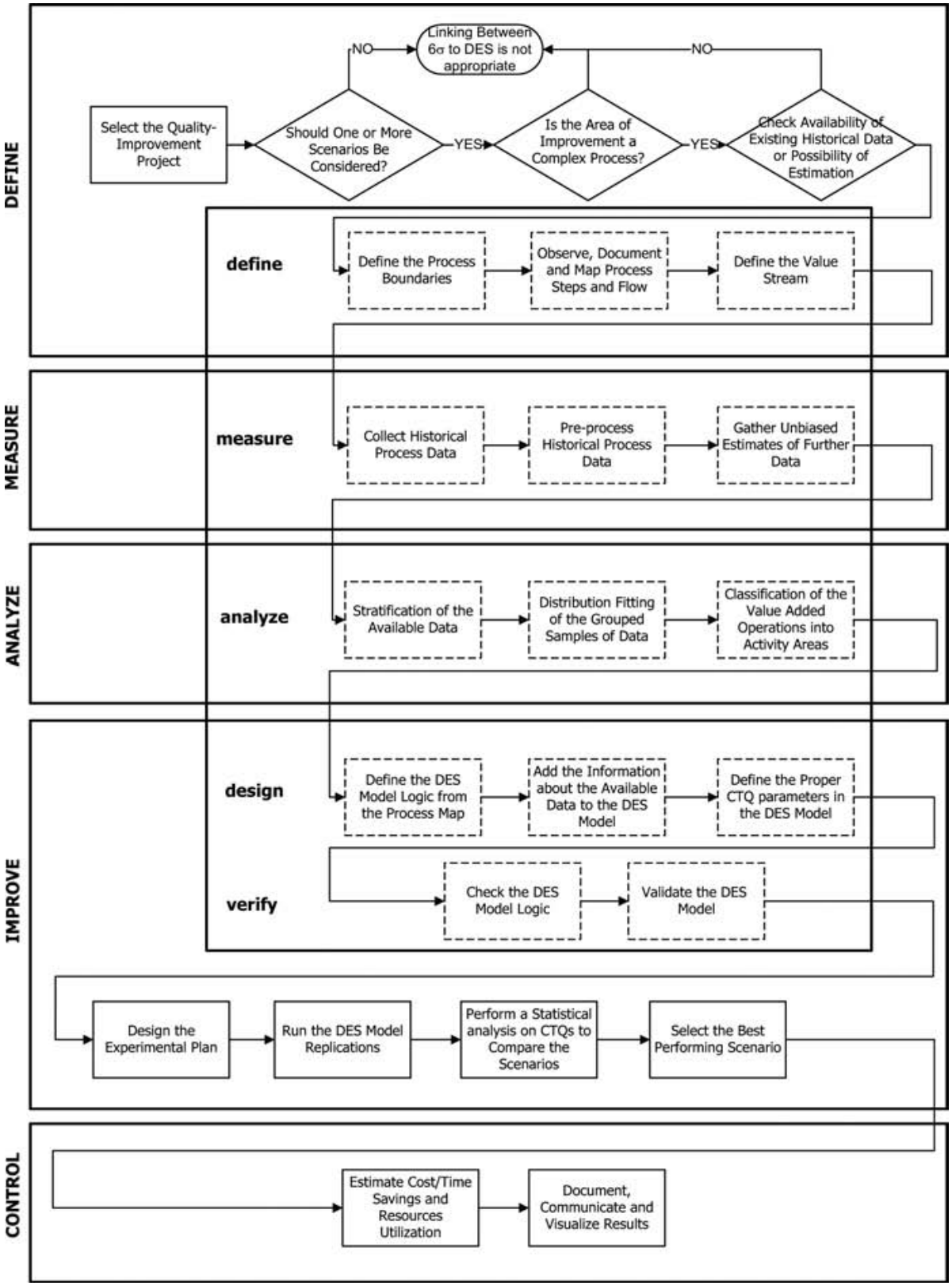
Within the roadmap, DMAIC procedures for a general quality improvement project "contained" the DMADV procedures that were related to the DES model design and development. While the upper case notation and plain line boxes denoted the phase and activities belonging to the outer DMAIC methodology, the lower case notation and dashed line boxes stood for the phase and activities of the inner DMADV methodology. (Celano et al., 2010)

The first stage of the outer DMAIC consisted of several steps for deciding whether the project was suitable for this roadmap. It included the inner define phase where a DES model was built to represent a current process flow. In the measure and analyze stage, the outer DMAIC overlapped the inner DMADV, and they both required relevant data collection and data distribution fitting. Once done with the data collection and analysis,

critical factors and performance measurements were embedded within DES models as variables or expressions. Then, different process configurations were compared. The executives could select the best scenario and document cost and time savings as calculated by the DES models. Finally, it was necessary to schedule brainstorming meetings for the sharing of information and opinions about the results; attendees would also discuss and plan how to organize for the implementation of the best process configuration. (Celano et al., 2010)

As discussed in the previous three sections, simulation modeling can be adapted to work alongside Six Sigma procedures, as well as lean principles. Plus, simulation modeling can be applied throughout a lean improvement event according to Robinson et al. (2012). Therefore, it can be concluded that these three methodologies are a good fit for analyzing various health care processes and can be adapted to each other, which shows promise to provide significant contributions to process improvement. Thus, one goal of this study is to develop a framework that combines the three in order to enhance their contributions and effects.

Figure 1: The Roadmap Linking Six Sigma and Simulation Model Development



(From Celano et al., 2010)

2.7 Summary

Phlebotomy has been practiced for centuries and is still one of the most common invasive procedures in health care (WHO, 2010). Each step in the phlebotomy process influences the quality of the specimen and is thus significant to the prevention of medical errors and to ensuring patient safety. Health care professionals and scholars have improved quality and efficiency in phlebotomy processes, e.g., lean (Morrison et al., 2011 & Melanson et al., 2009), and simulation (Rohleder et al., 2007 & Groothuis et al., 2002). Yet, when compared with other health care areas, the phlebotomy process lacks in quality improvement efforts. It can benefit from a systematic framework for process improvement, and the above mentioned literature has proven that lean, Six Sigma and simulation can serve that purpose.

What's more, lean, Six Sigma and simulation have been applied extensively in health care, offering structural procedures and principles in process improvement projects. They all aim to either improve the patient flow and satisfaction or increase the efficiency of hospital resources. Benefits of aligning these three through a phlebotomy process improvement project can be summed up as streamlined processes, efficient resources and breakthrough performance (Al-Aomar 2007).

As discussed above, bringing different methodologies together as one approach enhances their interactions and advantages. A value stream map from lean or a process map from Six Sigma can be well presented in simulation. The established Six Sigma procedures support simulation modelling with dependable input data, precise process details, and a prearranged approach for leading the analyses. In addition, simulation simplifies experimental design, what-if analysis, and the testing of alternatives. Using simulation modelling can reduce the cost and time of actual experimentation with the real system and provide a method to verify tested scenarios. Lean principles and tools, in a complementary role, assist to reduce waste and increase effectiveness. (Al-Aomar 2007)

Even though some researchers realize that using these three together can benefit quality improvement, few studies have used simulation for more than a decision-support tool

(Ferrin, Miller & Muthler 2005; Johnson et al., 2004) or done more than just focus on designing for Six Sigma (Al-Aomar 2006). There is a gap in the current literature: no process improvement approaches exist that structurally merge these three across an entire research. Furthermore, the flow time used in this paper as a performance measurement has rarely been studied in phlebotomy processes before. We also differ from others in introducing a new performance measure and applying a new combined framework to understand and improve the phlebotomy process. This paper also provides an innovative framework that can provide guidance for process improvement projects in phlebotomy and other healthcare processes.

3. Methodology

3.1 Six Sigma

As discussed in Yang and El-Haik (2003), two common frameworks are used in Six Sigma – DMAIC and DMADV. As mentioned earlier, DMAIC is used when rearranging or adjusting an existing process, while DMADV is concerned with the designing and implementation of a new process. This paper attempts to improve the phlebotomy process, and hence uses DMAIC, as phlebotomy is an already existing process. DMAIC has been briefly discussed earlier in this paper. What follows in this section is an elaborate discussion of the process. To start with, the DMAIC life cycle comprises the following five major stages:

- D-Define
- M-Measure
- A-Analyze
- I-Improve
- C-Control

Define

The first stage of DMAIC is Define, which consists of serial steps aiming to define the problem symptoms and identifying potential benefits of improvement. This stage requires focusing on the 'voice of customer'. It is important to determine the critical to quality (CTQ) factor from the customers' point of view. By understanding what is important to the customer, the goal of the whole project can be defined. Checking historical data is also useful for gaining insights into the process problem. Generally, meetings and interviews are two common tools used to gather data in this stage. People usually create a project team to act as major executors in the meeting and to carry out the improvement project. During the meetings and interviews, project scope, goals, and management commitment are usually defined to support the project. Finally, a project charter is always used to summarize the important elements of the project.

Measure

Once the project has been confirmed and approved, the next stage, which is Measure, proceeds to measure the existing process. Usually, it starts with observations of the process. A rough process map can be drawn after the first few observations. After learning more about the process, interviews with those who are directly involved with the process can help to create a correct and complete detailed process map. Then, a data collection plan based on the detailed process map can be created. When the data is collected and documented, it is time to continue to the Analyze stage.

Analyze

Assuming the measurement system is correct and precise, the preliminary data should be sorted out and analyzed. Building graphical plots can help to visualize the data patterns and trends. Also, some clues and ideas can be found and generated from the historical record. If applicable, statistical tests are performed to identify relationships. After gaining enough insights on the data, potential causes of the process problem should be categorized and discussed in the meetings or interviews. The project team can also use the "5 Whys" (continuously ask questions to explore the root cause of a particular problem – the '5' is the number of questions typically required to resolve the problem, which is derived from an empirical observation) or schedule brainstorm meetings to find out the root causes of the problem, which can then be examined to develop possible remedies.

Improve

Potential and possible solutions of the problem are generated in this stage. We can use brainstorm meetings, standard work or trail experiments to devise and evaluate different solutions. The best solution(s) can be chosen by conducting a regression or an ANOVA test. Reasonably foreseen and potential consequences should be discussed and explained before implementation of potential solutions.

Control

To sustain the gain from the Improve stage, the process needs to be controlled. Usually, control charts are built and used to monitor the CTQ of the process. On the control charts, the project team can note any unusual variation of the process with reasonable specifications that the project team decides upon. It may be necessary to modify and adjust the improved process if it is out of control. If the process is under control, there is no need to make changes. Lastly, the efforts and outcomes should be documented; these should be transparent to all staff members.

3.2 Lean

According to Womack and Jones (2003), lean thinking is categorized into five major principles:

- Value
- Value Stream Map (VSM)
- Flow
- Pull
- Perfection

These five principles lead a quality improvement project from problem identification to continuous improvement. Value requires the project team to focus on the 'voice of customer' and the standpoint of an entire process when defining project goals and critical to quality (CTQ) for the customer. These aspects are very similar to parts of the Define stage in Six Sigma. In this stage, regular meetings should be held during the whole project period. Interviews with front-line staff or customers help to define the value in the process.

The Value Stream Map (VSM) represents the beginning-to-end process. It consists of all types of activities and it helps in understanding the entire process flow and in identifying waste. An accumulated timetable helps to summarize the time and proportion that each of the three categories takes (value added activity, non-value added but necessary activity

and non-value added activity). The VSM along with a corresponding timetable is also the tool used in this principle.

After obtaining a complete VSM, it is easy to identify the waste within the process, which always are the non-value added activities. By eliminating this waste, a flow in the process can be achieved and the value added service/product can flow to the customer without delay and interruption. The non-value added but necessary activities need to be minimized as well. This can be achieved by downsizing the batch size, rearranging activity procedures or creating a standard workflow. Traditionally, the value added activities should be maximized to create more value for the customer. It is very important to speed up the value added activities without affecting the service quality. This is because, with the same output, the process efficiency increases when the flow time is less.

The fourth principle, Pull, means the process should not be started until the customer requests it. This is also considered as response to the customer. When the customer requests it, resources – i.e., nurse, medical laboratory assistant (MLA), tools – need to be ready for the process. By fulfilling that, the customer wait time for the service will be minimized.

Perfection is the last principle, and it that involves controlling and maintaining the significant efforts and improvements that are brought about by the previous four principles. It ensures that every step of the process undergoes constant review so that all activities within the process continue adding value to the customer. Usually, as the level of service and technology improves, many non-value added but necessary activities become completely non-value added activities. The first four principles, therefore, need to be revisited from time to time to ensure continuous improvement.

3.3 Simulation

Kelton et al. (2010) suggested eleven steps on how to conduct a simulation analysis, and illustrate several aspects of a successful simulation study.

First of all, a clear understanding of the system is essential. Usually, observations and interviews are tools used to understand the process. Being aware of what is happening, what the product (service in this study) is and how the process works are of paramount significance.

After getting enough knowledge of the process, the goal of improvement needs to be determined. It is necessary to be clear about what the process is now and to be realistic about what it can become, to specify the goal and the factors which can influence it, and to keep the goal in mind throughout the simulation study.

After gathering adequate information about the process and knowing what should be done, one can now formulate the model representation. Manually drawing a workflow diagram will help to build a logical progression of the model. The level of detail of the model should be decided upon with the managerial staff.

Once the model representation has been done, it is critical to accurately transfer it into a simulation software. One must make sure the model has been honestly and truly represented. Different skills of modeling may be useful; being familiar with the simulation software is also important to build and present the model logic.

The next step is to verify that the computer model represents the conceptual model correctly. It is usually in this step that the most extreme value of the input parameters is input into the model, and the output is verified to see if it is as expected. In addition to this, going through the logic of the whole model is also a necessary step in proper verification.

Model validation is the step that comes after verification. Validation is to make sure that the model adequately represents the real process. A comparison between the model data (input and output) and the real world data (usually the historical data) the way to validate the model.

After the model is verified and validated, different alternatives and factors are designed for the experiments. It is important to be clear about the goal and to plan out what is to

be analyzed. Factors and alternatives are usually generated in brainstorm meetings or in the interviews with those involved in the process.

Once a valid model is obtained, the experiments can be run. This step is to test the ideas or the alternations generated to find the possible improvement to the process. One must take care in choosing the number of replications to get representative results; the computer may need hours to run a complicated model.

After getting results from running the simulation model, an analysis should be conducted to find the best solution for the process problem. Various statistical tests (e.g. ANOVA) can help to determine or identify the best solution.

The next step is gaining insight from the model. Any ideas generated from the results, any recommendations other than the alternatives already considered and any implications suggested by the results should be considered and discussed carefully.

Lastly, one may choose to document what has been done. This is not only good for the existing process, but also beneficial for future process improvement. In addition, the documentation is an essential point to convince management to support the implementation.

3.4 The Complementarity of Six Sigma, Lean and Simulation: a Theoretical Perspective

For the purpose of this study, the three methodologies need to be used together. In order to do so, we need to consider how to align them in a rational and logical way. The Six Sigma structured DMAIC procedure is expected to enhance product (service) quality and performance. Multiple managerial and technical tools are used in both product and service improvement endeavors. A successful Six Sigma improvement project is closely related to the effectiveness of using different tools (Ahire & Dreyfus 2000). Similarly, lean thinking involves using different principles and tools and it is believed to help product (service) quality improvement. The complementary relationship between Six Sigma and lean is well established. Not only do both aim to eliminate waste and variations to

improve the product (service) quality, they also focus on lowering the cost and increase the efficiency using DMAIC procedures or the 5 lean principles (Salah, Rahim & Carretero 2010). In the pursuit of satisfying customers and gaining financial benefits, researchers have been advised to use Six Sigma and lean together instead of only one of them, to reduce shortcomings and cope with market changes (Antony 2004; Hines, Holwe & Rich 2004; George 2003).

Simulation, the third methodology under consideration, provides a platform for Six Sigma and lean to enhance their advantages to the utmost by providing a computer-based and inexpensive environment. The major contribution of simulation is the ability to correctly represent the dynamic and complex features of a real-world system (process), and it has evolved over time for Six Sigma and lean improvement (Al-Aomar 2006). In addition, a good simulation model can borrow from and/or work hand-in-hand with Six Sigma and lean to provide a clear understanding of the system (process) and generate potential alternatives. In this research, the eleven steps of building a simulation model will be included in a Six Sigma and lean framework.

We have reason to believe that combining the different methodologies as one approach enhances their interactions and advantages and can provide insights that one methodology cannot provide. For instance, the first stage of Six Sigma (define), the first principle of lean (value) and the first two steps of building a simulation model (understand the system and be clear about the goal) are related to each other because they have the same goal, which is to focus on the 'voice of the customer' and the tools to achieve it, such as observations, interviews and meetings. A Six Sigma process map and a lean value stream map can be built in the simulation environment, which is easy to modify and interpret. The structured Six Sigma procedures and lean thinking support the simulation modelling with dependable data input, precise process details, and a prearranged approach for analyses. Furthermore, simulation simplifies experimental design by providing a what-if study and alternative estimations. Cost and time of actual experimentation of Six Sigma and lean improvement can be reduced and a visualized change of the system (process) also helps to verify tested alternatives (Al-Aomar 2007).

4. A Synthesis of Lean, Six Sigma and Simulation

This framework developed for this study is organized around the 5 DMAIC Six Sigma procedures, integrating the lean principles and tools and the simulation modeling steps within the DMAIC procedure. This section explains the work done in this study, including the problem definition, data collection, analysis, and findings. In the following section, the framework is presented and the generalizability of the methodology is discussed.

4.1 Define

The define stage begins with understanding the Phlebotomy Process in the ED of the St. Catharines Site of the NHS. Carried out by both nurses and Medical Laboratory Assistants (MLA), the phlebotomy process in the ED of the St. Catharines Site is highly variable and complex (as explained above and elaborated on below).

This is a new process and has only operated since March 2013. Even though the nurses and MLAs are well trained and qualified to conduct the process, they do not have the time to step back and analyze its' efficiently. The procedures they use are at times based on their own personal preference. The existing way in which they carry out the process creates many chances for interruption and a lot of opportunities for delay.

In the ED of the St. Catharines Site, newly arrived patients are sent to Urgent Care (UC) or Emergency Room (ER) at the triage depending on how serious their situation is:

UC (Urgent Care): patients that need medical attention but are not in a life-threatening state

ER (Emergency Room): very sick patients that have recently arrived (their injuries or condition are life-threatening)

Generally, the ER patients have blood drawn by ER nurses. If they have difficulty in drawing the blood, the nurse will call an MLA from the lab to assist them, but generally, the phlebotomy process of ER patients is carried out by the ER nurses only.

For the UC patients, the phlebotomy process involves both a UC nurse and an MLA. The nurse takes the order from the doctor and prints out the labels, and then calls the MLA to draw the blood.

The preliminary process maps for UC and ER patients are shown in Figures 2 & 3.

Figure 2: UC Patient Preliminary Process Map

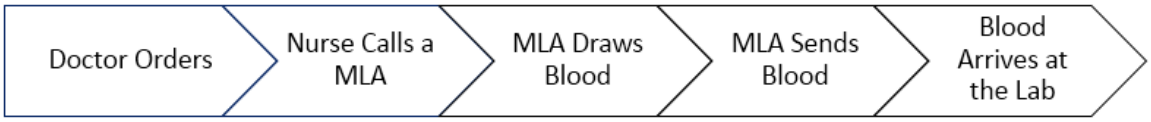
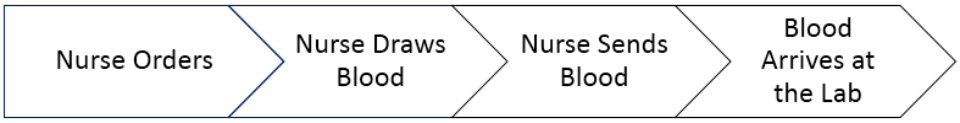


Figure 3: ER Patient Preliminary Process Map



The ER phlebotomy process starts at the time an ER nurse orders a blood test (hospital staff call this a 'medical directive') and ends when the specimen arrives at the lab.

For the UC patient, the blood test is ordered by the doctor. A UC nurse enters the order into the system and prints labels, then (s)he calls an MLA to the UC and lets the MLA finish the rest of the process.

Performance Measurement

Even though the procedures of the ER and the UC phlebotomy processes are different, the calculation of their average flow time is the same. These times are also the performance measurements in this study, formulated as follows:

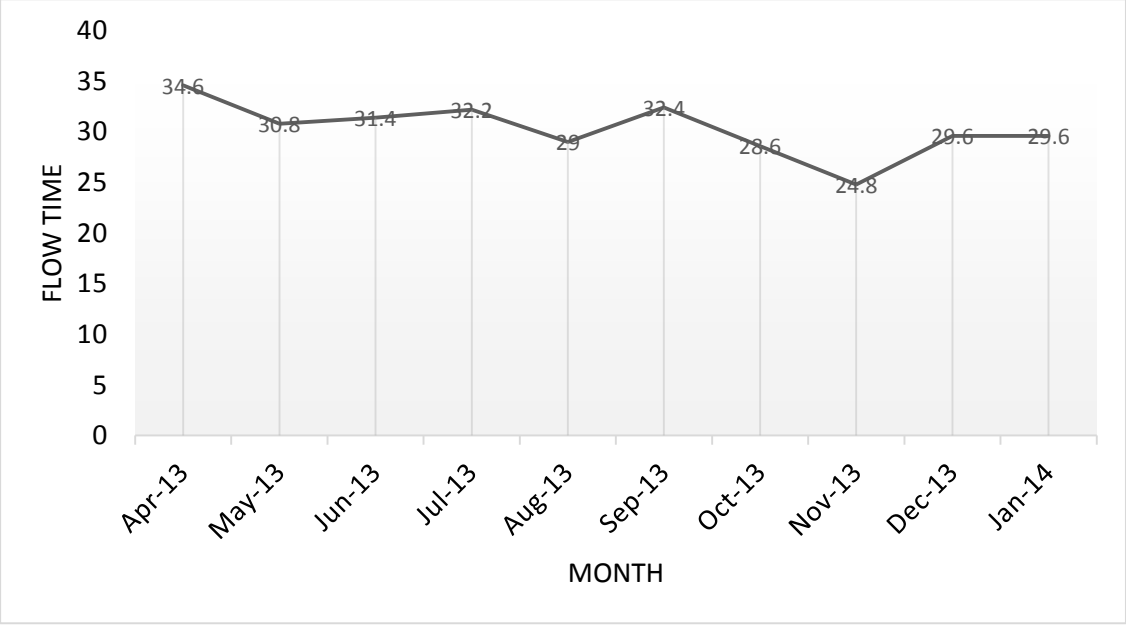
$$Y = \frac{\sum_1^N (T_N - S_N)}{N} \quad (1)$$

where: Y = Average flow time
T_N = Process end time: Time specimen arrives at the lab
S_N = Process start time: Time doctor finishes writing order
N = Sample size

The phlebotomy process at the St. Catharines Site currently experiences an unexpectedly long flow time. As will be shown later, this is because of the delays and interruptions within the process.

Ten months of data was pulled out from the hospital data base. In these 10 months (from April 2013 to January 2014, Figure 4), the average flow time of all new ED patients (includes ER and UC patients) is 30 minutes, with a range of less than 10 to more than 120 minutes. Note that in the hospital records the flow time starts when a blood order is finished entering into a computer, and ends when the lab receives and scans the blood specimen. However, as mentioned before, we study the phlebotomy process starting when a doctor/nurse orders a blood test, and ending when the lab receives and scans the blood specimen. Therefore, the flow time recorded by the hospital is just part of the flow time that we collect and analyze later. We also collect the difference between the two ways of measuring (through observation) and will report it later in the Measure stage. Note that this data is from the Hospital's Historical Records and the historical data of all new ED patients cannot be separated into UC patients and ER patients because of the hospital system's limitations. Figure 4 shows the average flow time per month from the hospital's data.

Figure 4: Average Flow Time per Month (in minutes)



In a dedicated phlebotomy station, it is the patient that comes to the nurse or MLA to have the blood drawn, and the nurse or MLA does not need to walk to the patient. In that case, a nurse or MLA can draw blood from 10 patients in an hour. This means the actual work required for the phlebotomy process can be finished within 6 minutes. Although the setting and operational constraints in the ED of the St. Catharines Site is different and it is the nurse or MLA who has to go to the patient to draw blood from them, the 30 minutes-average flow time is still excessively high and improvements should be possible.

The tools and methods we use in this Define stage are meetings, observations, interviews, and obtaining the hospital data. Meetings were held before and after the observations and interviews. Participants of the meetings included the lab manager, the ED manager, the quality department advisor and the quality department assistant. The historical flow time data (Figure 4) were provided by the lab manager. The project scope, management commitment and preliminary process maps (Figure 2 & 3) were discussed and approved during the first meeting. A general project agenda and approximate data collection period were also determined at the same time. Initial observations of the processes and informal interviews with nurses and MLAs were conducted a week after the first meeting.

In the Define stage, thinking from the point of view of the 'customers' is required by both lean and Six Sigma. In this study, the 'customer' is both the hospital and the patient. From the hospital's point of view, a long flow time will decrease resource productivity (e.g. number of patients that are serviced in an ED room). The number of patients waiting in line will increase and patient length of stay in the ED will be extended as well. While we are focusing on the process in the ED, delay of medical diagnosis and increased waiting time are two direct consequences of long flow time. Therefore, the CTQ in this study is finalized to be the flow time and one of the goals is to reduce the flow time to 20 minutes. A project charter including a problem statement and project scope summarizes the goals and management commitment of this study (Table 1).

Table 1: Project charter

Project charter
Proposal for process improvement in the phlebotomy process
Problem statement: The phlebotomy process at the ED is an important factor in medical diagnosis. In the ten months from the opening of the new St. Catharines Site, the ED phlebotomy process has experienced long flow time. This has caused patients to wait and has decreased resource productivity. For example, the long flow time will increase the waiting time of the next patient who needs the nurse or MLA to draw their blood. The MLA productivity will decrease if (s)he needs to wait for the patient to be ready, or for the labels to be generated.
Description: The current flow time of the process is 30 minutes on average. It is unclear why the process takes so long even though it only has a few steps. The performance indicator is the flow time.
Project scope: The scope of this study is limited to the ED in the hospital. It involves the ED phlebotomy process, which starts when the blood test is ordered and ends when the specimen arrives at the lab. It excludes the analysis process within the lab.
Goals: 1. Understand and improve the ED phlebotomy process (mainly to reduce the flow time to 20 minutes or less) 2. Combine lean, Six Sigma and simulation to create a new framework for the ED phlebotomy process 3. Create a general framework for other health care process improvements
Management commitment: Even though this study does not actually have a research team with hospital staff in the normal sense that a lean/six-sigma project would have, the Lab Manager, ED Manager and two Hospital Quality Advisors all support and provide assistance to this study. We have had meetings together to discuss the process problems and decided on the process performance measurement and goals. They also provided available data and have facilitated access to the locations where data is to be collected.

4.2 Measure

In the measure stage, it is critical to use proper and correct methods to collect data, some of which are similar to those used in the Define stage, but with more detail. Interviewing is used initially to gain insight into the process and determine which data is relevant.

Informal interviews with nurses and MLAs were carried out during the observation and data collection. The purpose of the interviews was to gather enough information about the phlebotomy process as well as staff activities between steps.

Detailed process maps (Figure 5 & 6) were developed, extending from the preliminary process maps during the observations. Also, informal interviews with nurses and MLAs helped to clarify the terminologies and confusions within the processes. These process maps depict the detailed procedures within each process, and they are used to determine the points in time to record during the time study portion of the data collection.

Note that there is an alternative procedure for the ER patient, where the nurse enters information and prints out labels after (s)he collects the blood. This procedure is used as frequently as the one in Figure 6. However, it is not the procedure that the hospital recommended and thus is not shown here, but it will be one of the alternatives that is tested in the simulation later.

Figure 5: UC Patient Detailed Process Map

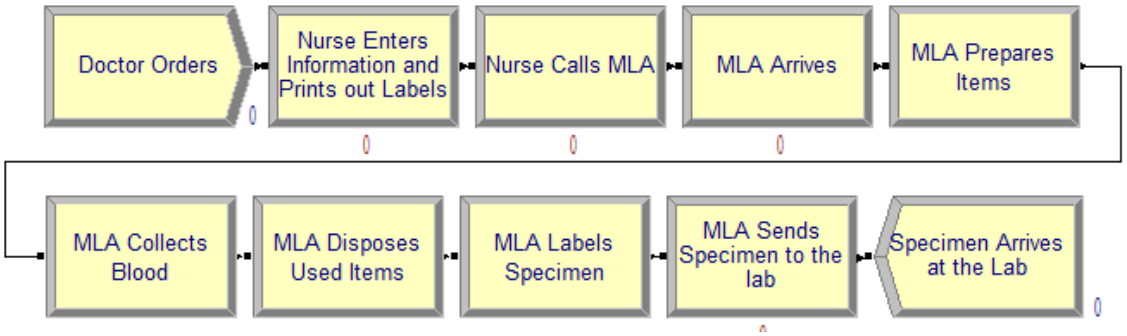
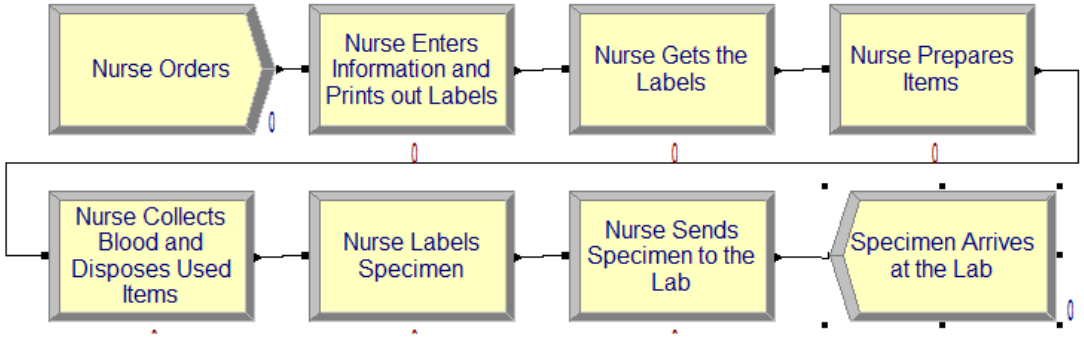


Figure 6: ER Patient Detailed Process Map



According to the process maps, two time studies are carried out to collect the relevant data (listed below). We record the time when the order is taken, how long each step takes and the time gap between steps. Then, by using the accession code of the specimen (obtained from the hospital), the time when the specimen arrives at the lab can be determined.

For UC patients, time stamps for the following activities are collected:

- Doctor orders
- Nurse begins entering information
- Nurse finishes entering information, which includes sending the command to print the labels
- Nurse begins calling MLA
- Nurse finishes calling MLA
- MLA arrives and gets the labels
- MLA begins preparing items
- MLA finishes preparing items
- MLA begins collecting blood
- MLA finishes collecting blood
- MLA begins disposing used items
- MLA finishes disposing used items
- MLA begins labeling specimen
- MLA finishes labeling specimen
- MLA begins sending specimen to the lab
- MLA finishes sending specimen to the lab
- Specimen arrives at the lab

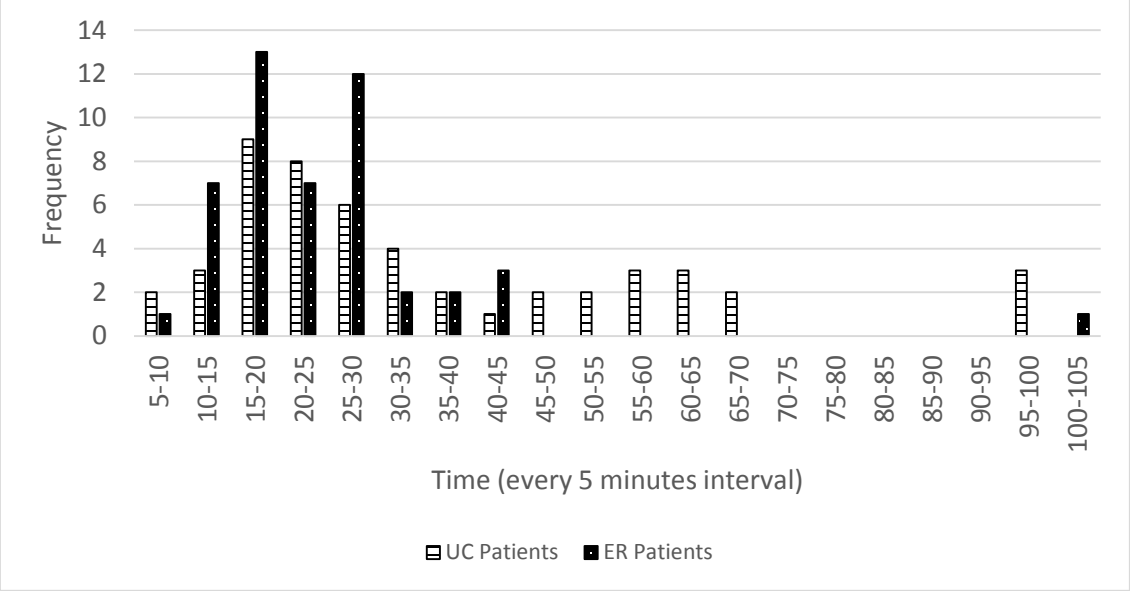
For ER patients, time stamps for the following activities are collected:

- Nurse orders
- Nurse begins entering information
- Nurse finishes entering information, which includes sending the command to print the labels
- Nurse gets the labels
- Nurse begins preparing items
- Nurse finishes preparing items
- Nurse begins collecting blood
- Nurse finishes collecting blood, which includes disposing used items
- Nurse begins labeling specimen
- Nurse finishes labeling specimen

- Nurse begins sending specimen to the lab
- Nurse finishes sending specimen to the lab
- Specimen arrives at the lab

Because the UC and ER patients are in two separate areas, we collected the data over two different periods. The UC patient data was collected from January 4, 2014 to January 11, 2014 (8 days, 47 hours). For the ER patients, the data were collected from January 12, 2014 to January 19, 2014 (8 days, 56 hours). The average flow time (Figure 7) is 30 minutes for UC patients (sample size 50) and 27 minutes for ER patients (sample size 48).

Figure 7: Flow Time Frequency (5 minutes intervals)



Compared with the historical data, the flow time we collect is shorter. We consider this as a reasonable difference because the nurse or MLA may perform the process faster when being monitored (Hawthorne Effect). Although the researcher tried to be "invisible" by maintaining distance from the nurses and MLAs, their assistance was necessary at times for clarification of which step they were doing; thus, they knew they were being monitored.

With the help of the detailed process maps and spending approximately one hundred hours monitoring the processes, the time spent on each activity and the delays between were quantified. Then, the detailed process maps were combined with the collected data

to create two value stream maps (VSMs) (Figures 8 and 9) and Process Activity Tables (Tables 2 and 3) to identify waste within the processes. All activities are classified into the three aforementioned categories of lean: value added (denoted in grey), non-value added but necessary (denoted in white) and non-value added (denoted in black).

Figure 8: UC Patient Value Stream Map (VSM)

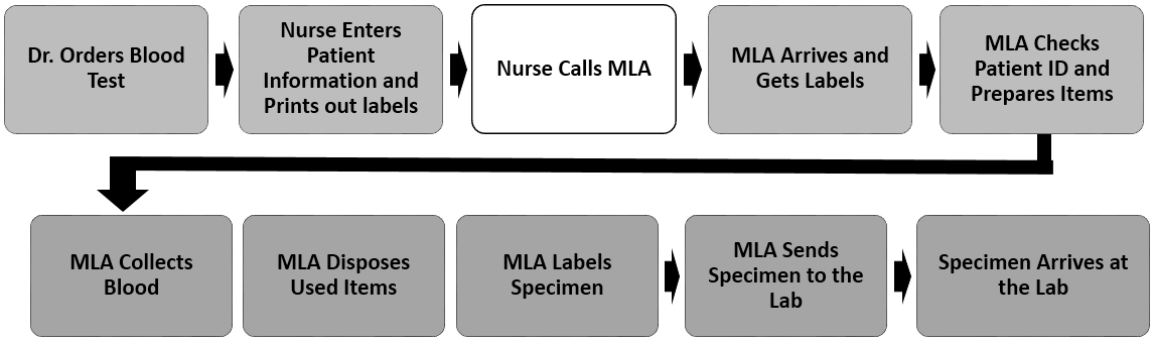


Table 2: UC Process Activity Table

	Activity	Time	Accumulated Time	Percentage	Accumulated Percentage
Value Added	Dr. Orders Blood Test*	/	/	/	/
	Nurse Enters Patient Information and Prints out labels	2'16''	2'16''	6.47%	6.47%
	MLA Arrives and Gets Labels*	/	/	/	/
	MLA Checks Patient ID and Prepares Items	50''	3'06''	1.50%	9.16%
	MLA Draws Blood	2'05''	5'11''	6.14%	15.29%
	MLA Disposes Used Items	23''	5'34''	0.69%	15.98%
	MLA Labels Specimen	50''	6'24''	1.50%	18.68%
	MLA Sends Specimen to the Lab	36''	7'	1.08%	20.95%
	Specimen Arrives at the Lab*	/	/	/	/
Non-value Added But Necessary	Nurse Calls MLA	26''	7'26''	0.78%	21.73%
Non-value added	Delay between Dr. Orders and Nurse Enters Information	2'40''	10'06''	7.96%	33.36%
	Delay between Nurse Enters Information and Calls MLA	2'27''	12'33''	7.53%	40.88%
	Nurse Waits For MLA	9'53''	22'26''	31.60%	73.81%
	Delay between MLA Arrives and Prepares Items	1'40''	24'06''	4.64%	79.77%
	Delay between MLA Prepares Items and Draws Blood	10''	24'16''	0.33%	80.11%
	Delay between MLA Labels Specimen and Sends Specimen	17''	24'33''	0.56%	80.67%
	Time of Specimen in the Tube System to the Lab	5'43''	30'16''	18.00%	100.00%

*Asterisks represent steps with no duration-only a time stamp

Table 2 presents these categories for the UC patients. The actual value added time is 7 minutes; the non-value added but necessary activity (i.e., 'Nurse Calls MLA') takes 26

seconds; the non-value added activities, which are the delays between the activities (i.e., wait time and travel time) account for 24 minutes, occupying more than 70% of the total flow time.

Figure 9: ER Patient Value Stream Map

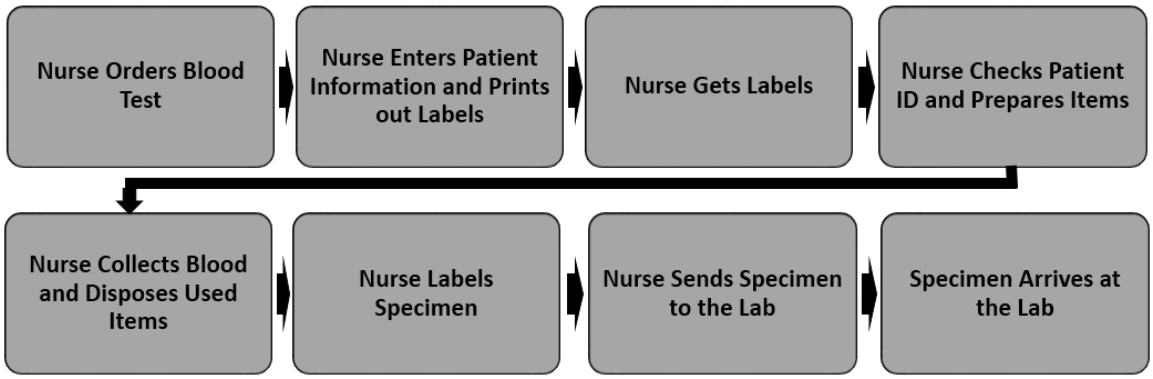


Table 3: ER Process Activity Table

	Activity	Time	Accumulated Time	Percentage	Accumulated Percentage
Value Added	Nurse Orders Blood Test *	/	/	/	/
	Nurse Enters Patient Information and Prints out Labels	1'50''	1'50''	5.34%	5.34%
	Nurse Gets Labels*	/	/	/	/
	Nurse Checks Patient ID and Prepares Items	59''	2'49''	2.10%	8.86%
	Nurse Draws Blood, Disposes Used Items	4'33''	7'22''	15.41%	25.70%
	Nurse Labels Specimen	1'21''	8'43''	4.31%	30.01%
	Nurse Sends Specimen to the Lab	28''	9'11''	1.00%	32.43%
	Specimen Arrives at the Lab*	/	/	/	/
Non-value Added	Delay between Order and Enter Information	3'43''	12'54''	12.63%	46.19%
	Delay between Enter Information and Get Labels	1'43''	14'37''	5.27%	52.93%
	Delay between Get Labels and Prepares Items	2'33''	17'10''	8.58%	62.98%
	Delay between Prepare Items and Draw Blood	30''	17'40''	1.10%	64.09%
	Delay between Draw Blood and Label Specimen	3'33''	21'13''	12.27%	77.83%
	Delay between Label Specimen and Send Specimen	1'09''	22'22''	4.01%	81.84%
	Time of Specimen in the Tube System to the Lab	4'53''	27'15''	16.69%	100.00%

*Asterisks represent steps with no duration-only a time stamp

Table 3 shows the value categorization of the ER activities. The value added activities take more than 9 minutes. In the ER patients' case, there are no non-value added but necessary activities. However, the non-value added activities take 19 minutes and should be eliminated if possible.

After determining the activities within the process, the value stream maps were transferred to the Arena Software. We verified and validated the value stream maps within Arena until they are ready to be analyzed.

4.3 Analyze

Nine months of historical data was obtained from the hospital's database that shows the number of patients registered, by hour, in the ED (Figure 10). This information was initially used to give a general picture of workload level in the ED. It is found to be consistent with the blood order frequency data from the lab database (Figure 11).

Figure 10: ED Average Visits by Registration Hour

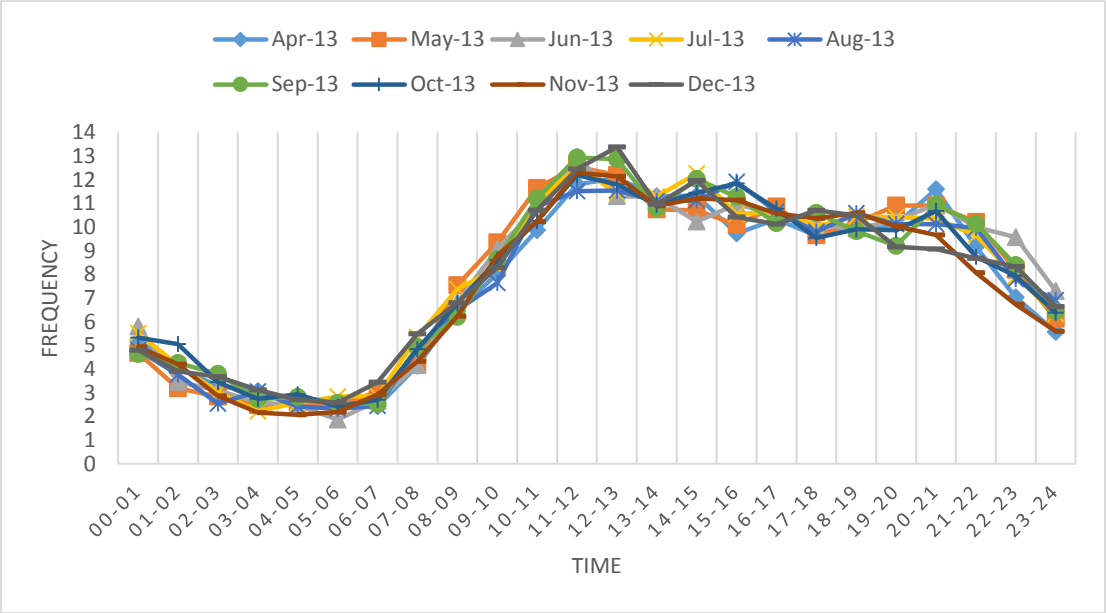
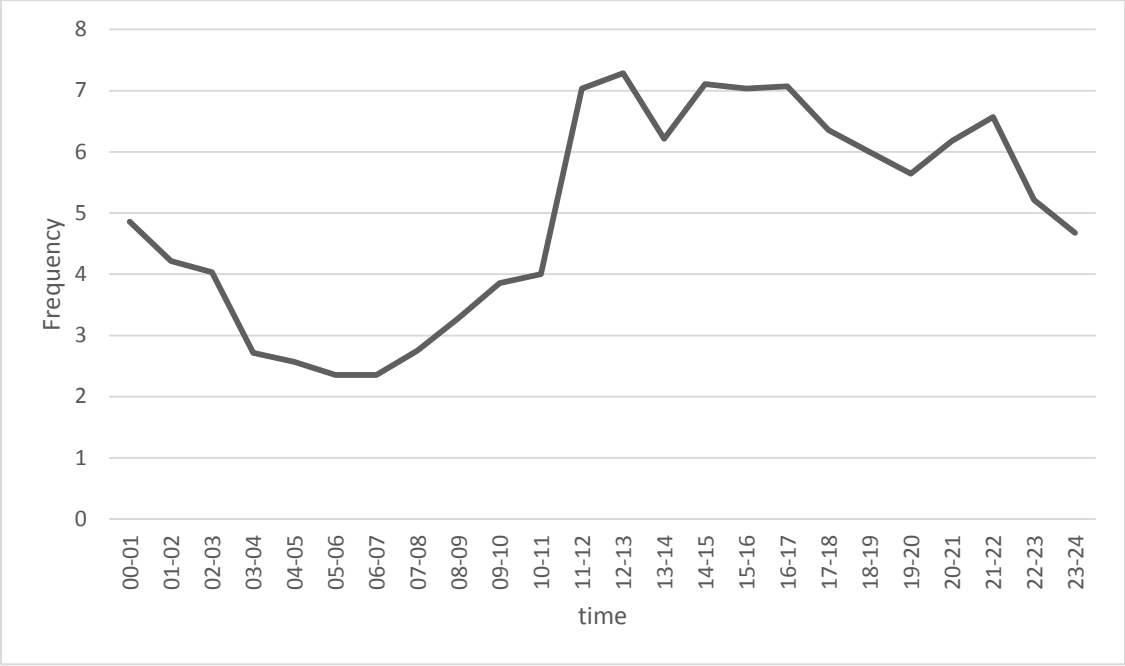


Figure 10 shows that the busy hours in the ED usually start around 11 AM and end about 10 PM. During these 11 hours, the rate of patient registration in the ED is 10.76 per hour; the standard deviation is 1.02. In the non-busy hours (10PM-11AM), the average registered number of patients per hour is 5.22, and the standard deviation is 2.62.

Figure 11: Average Blood Order Frequency per Hour (Hospital Lab, January 2014)



From Figure 11, the average number of blood orders in January during the busy 11 hours is 6.5/hour; and they represent 61% of the total blood orders in a day.

The ED registered patients include UC patients, ER patients and RAZ (Rapid Assessment Zone) patients. The RAZ patients are separated to improve the patient flow in the ED, and are different from the UC and ER patients. The RAZ patients are counted in the ED registration and the January 2014 blood order data, but they are not included in this study. Therefore, if we want to validate our data by comparing with the hospital's historical data, we need to exclude the RAZ patients.

In order to do so, we need to have more information on ED and RAZ patients. Each area in the ED has a nurse's desk located in the centre, called a "front desk". This front desk is very close to all the patient rooms it is meant to serve, and should not be confused with the admissions desk where patients register upon their arrival to the ED. Over every front desk in the ED, there is a tracker that is used to keep track of the type of ED patient, their status and the room they are in. It shows the patient's symptom and the stages, which could be 'doctor assess', 'nurse assess', 'X-ray', 'lab', etc. The tracker also shows if a patient is waiting for blood collection or waiting for a blood test result. When we were

collecting the data in the UC and the ER, we were able to tell from the tracker how many RAZ patients were being served and how many of them needed to do blood tests. Usually, there were 3 to 4 rooms allocated for RAZ patients. The rooms are always full with patients waiting.

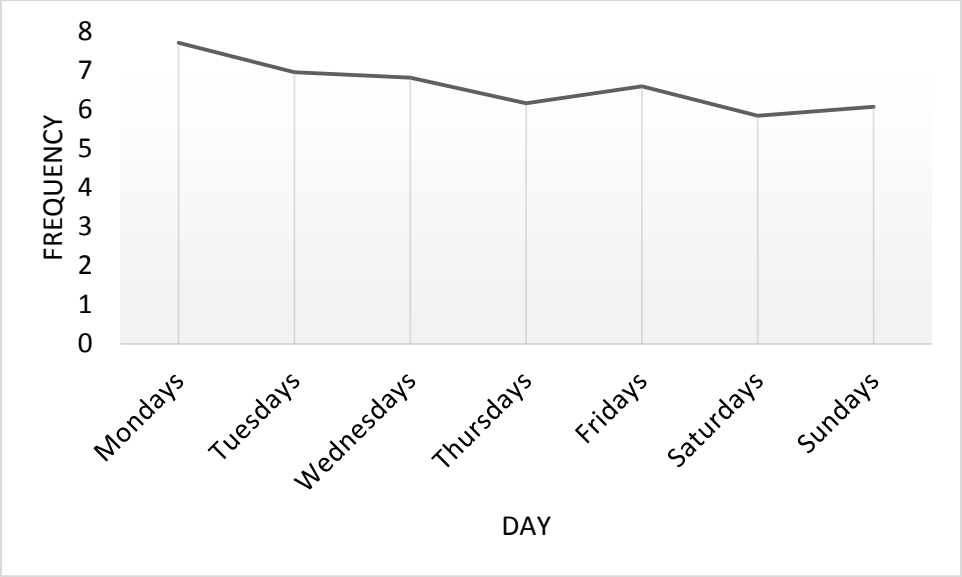
Additionally, after having discussions with hospital staff about RAZ patients, we can assume that there are at least 2 blood orders per hour for RAZ patients during the busy hours. Therefore, the blood order data collected from our observations should have a lower number of blood orders than compared with the hospital's data. Therefore, we assume that there are approximately 4.5 (6.5-2) blood orders per hour for UC and ER patients.

Furthermore, within the ED of the St. Catharines Site, there are five areas for ER patients: A, B, C, D and E pods. Most of the new patients go to the A pod or B pod. The C, D and E pods are for the patients with special concerns (e.g. mental disease, sexual assault or admitted patients), and they are not included in this study. The only difference between the A pod and the B pod is the number of rooms for patients. The A pod is a slightly larger with 24 rooms, while the B pod has 17 rooms.

Note that all the ER time study data (including order interval time) was collected from the B pod. The phlebotomy process in the A pod is the same as in the B pod. For the simulation models, the blood order interval time in the A pod will be adjusted slightly lower than was found in B pod, based directly on the number of rooms.

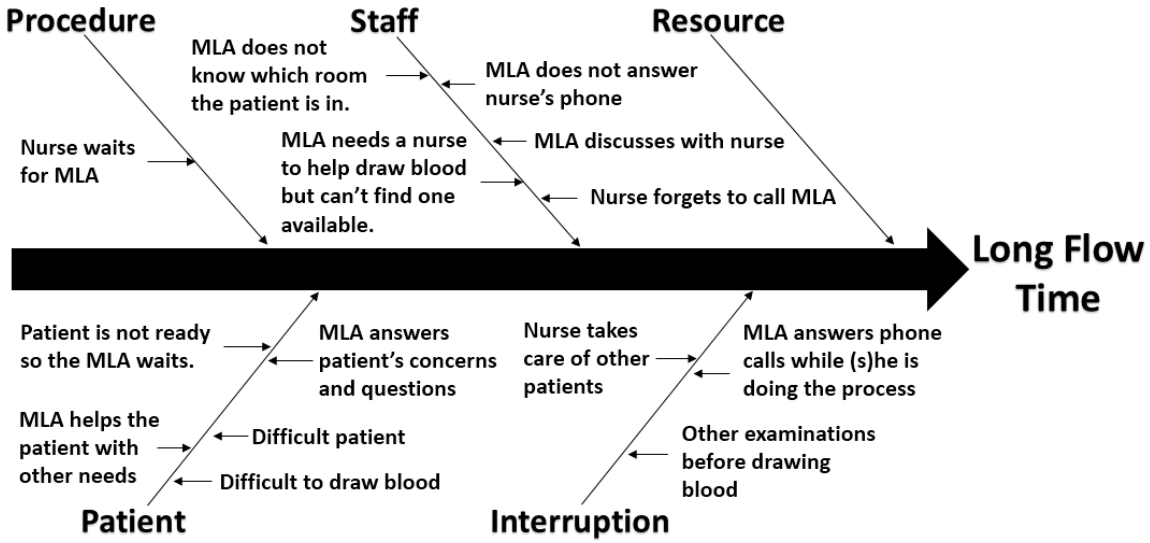
In addition, the daily blood order frequency data (Figure 12) show that Monday is the busiest day of the week; it reaches almost 8 orders per hour during the busy hours. The other days have an average of 6.4 orders/hour. We also find that weekdays (6.8 orders/hour) are busier than weekends (5.9 orders/hour).

Figure 12: Average Number of Blood Orders during the Busy Hours (11 AM to 10 PM)



From the process observations and informal interviews with hospital staff, cause and effect diagrams were created (Figure 13 & 14). They show all the delays in the process that occurred during observations, grouped under five categories: Procedure, Staff, Resource, Patient and Interruption. Ideally, if we can eliminate all these causes, there will be no delays or interruptions within the process.

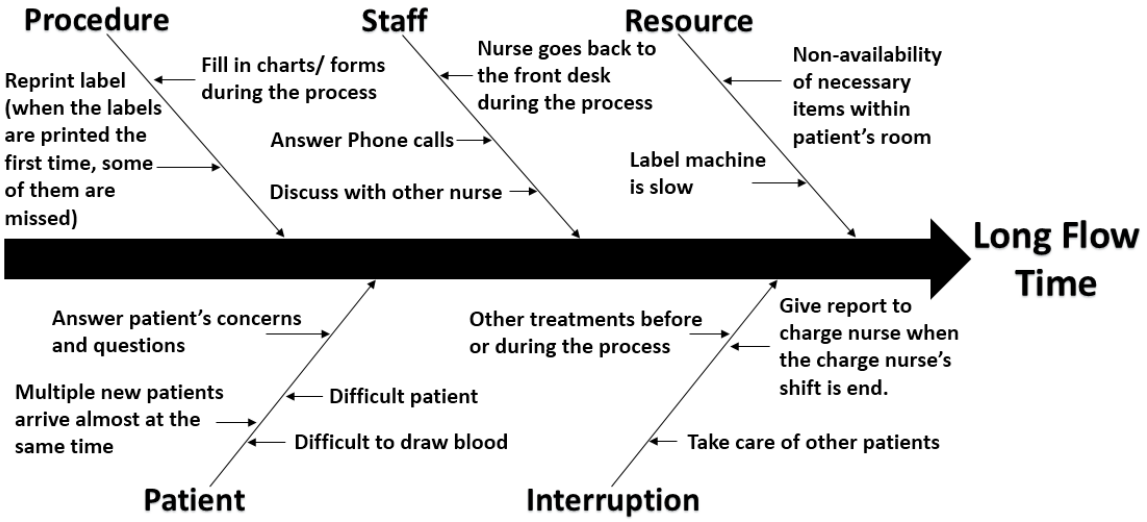
Figure 13: UC Patient Cause & Effect Diagram



Compared to the ER patients, the UC patients only have four categories of causes, since there were no Resource problems observed for the UC patients.

However, the slow label printing for ER patients may create delays for UC patients in the future as well. This is because UC and ER patients have the same kind of label printing machine and share the same kind of computer module and in the current process of UC patients, a UC nurse needs to call and wait for an MLA after (s)he finishes entering information and prints out labels. Therefore, the delay caused by the label printing machine does not attract attention as it takes place during the wait for the MLA – it does not affect the flow time of UC patients in the current process configuration, but it must be kept in mind that this may become a cause of delay for UC patients if there is a change in the process.

Figure 14: ER Patient Cause & Effect Diagram



To further analyze the causes of delay, two Pareto charts showing the frequency of the causes and their accumulated percentages are developed (Figures 15 & 16). It would be an ideal situation if we could address the most common cause first and then attend to all causes according to the descending order. However, this is not applicable for this study. As we see in the charts, there are two different bars. The white bars represent the causes that add value to other hospital processes; therefore, the hospital management does not want these reduced. It may be possible to do some of these at different times (e.g. after the phlebotomy process) or more quickly, but this is beyond the scope of this study since

it depends on the relative priorities the hospital places on these tasks. Therefore these will not be studied further, and we will focus on solving the black ones.

Figure 15: Pareto Chart of Long Flow Time Causes for UC Patient

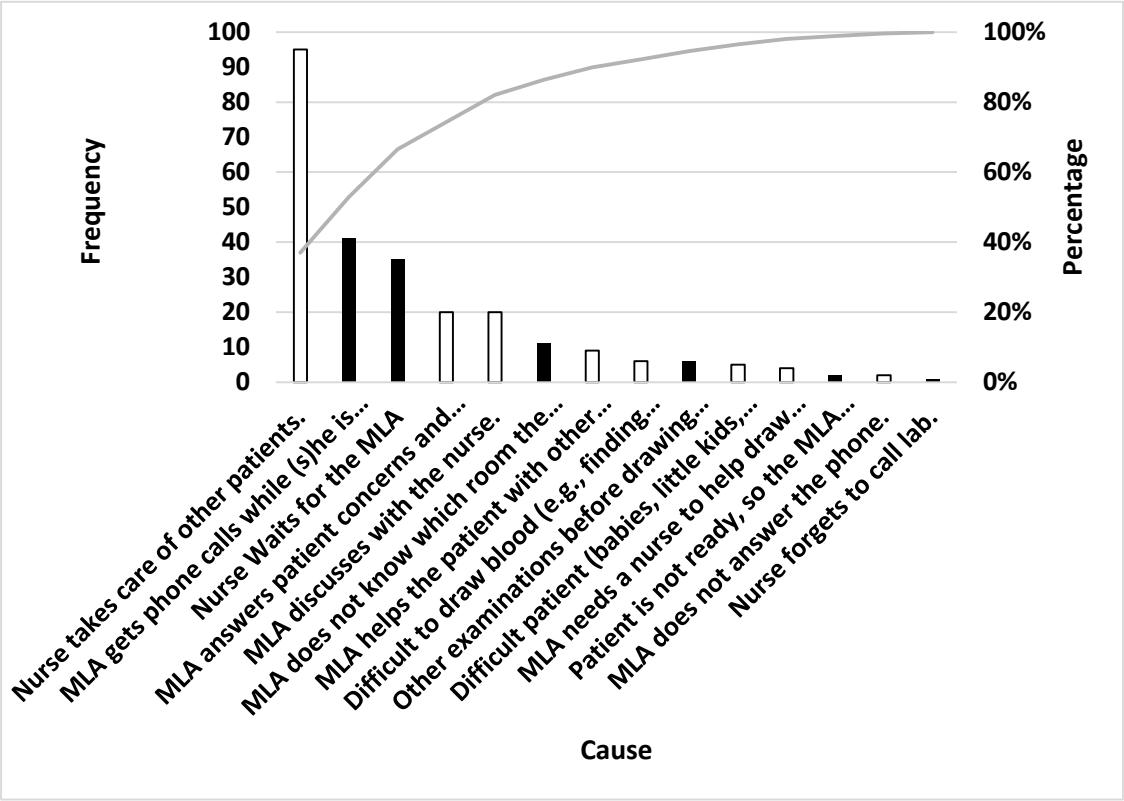


Figure 15 shows that for UC patients, the most common cause identified is that the 'Nurse takes care of other patients'. In the UC of St. Catharines Site, there are two nurses from 11 AM to 11 PM and one nurse from 11 PM to 11 AM. The maximum number of patients they can take care of is 13 (because there are 13 rooms in the UC), and it is always operating at full capacity during the busy hours. When the doctor orders a blood test for a patient, (s)he writes down the order on the patient's chart and then puts it into a 'doctor-order' basket for a nurse to check and fulfill the order. However, as there are always multiple patients in the UC demanding the nurses' attention, the nurses usually are occupied by several patients concurrently (e.g. doing treatments on other patients), and therefore cannot undertake the 'doctor-orders' right away. As mentioned before, this adds value to other hospital processes and therefore is not a matter of concern for the hospital.

The second most common cause is that 'MLA gets phone calls while (s)he is doing the phlebotomy process'. The hospital's policy requires every MLA to carry a cellphone. They must answer or return every phone call because that is how they get the blood orders. If they miss a call, they must call back as soon as possible. Although they are not required to answer calls from the lab manager while they are serving a patient (they can call back after they finish), not all the MLAs follow this; they sometimes stop the process to answer the calls.

The 'Nurse waits for the MLA' is the third most common cause of long flow time in the UC. As we know from the process map, the third step in the process is 'Nurse calls MLA'. After that, the nurse has to wait for the MLA to come and collect blood from the patient. Usually the MLA is somewhere in the hospital or in the lab, so it takes him/her some time to get to the UC; sometimes when (s)he is dealing with other patients, it takes even longer.

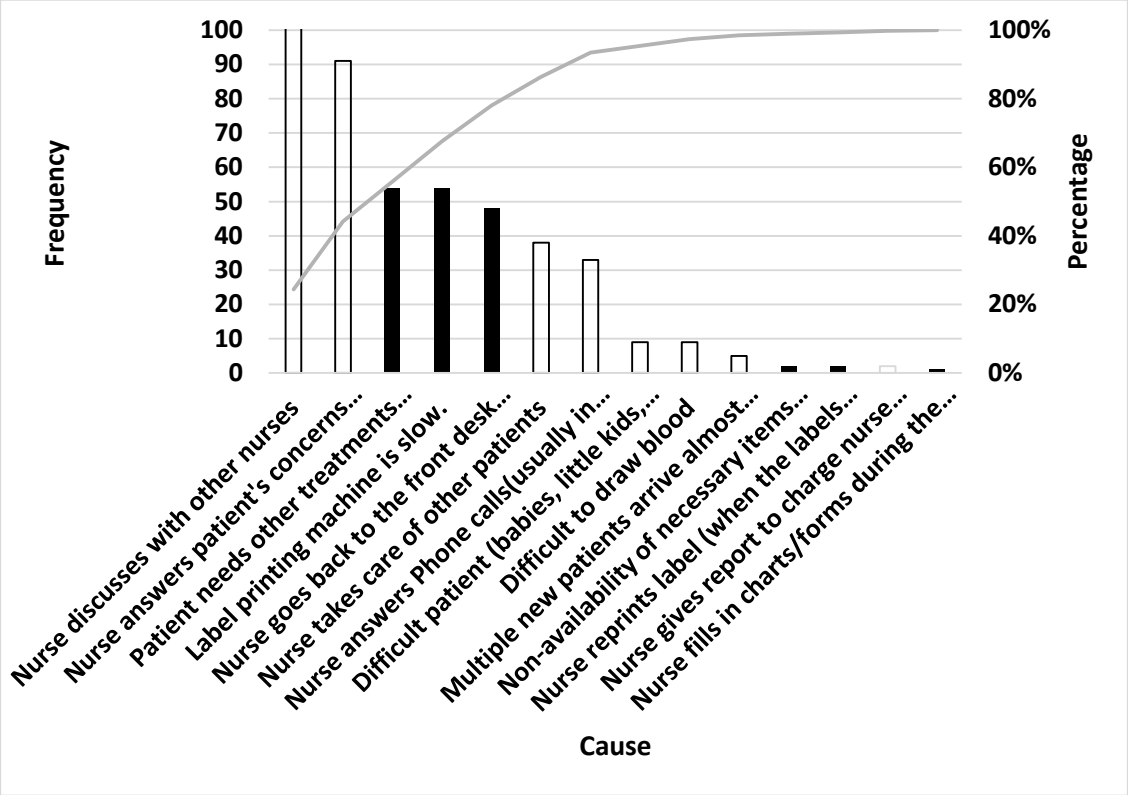
As we know that the fourth and fifth causes are not the concerns of the hospital, we focus on the sixth cause, which is the 'MLA does not know which room the patient is in'. This happened 11 times during our observations. When the MLA arrives at the UC, (s)he usually gets the labels and then goes directly to the patient's room. However, sometimes the MLA does not know which room the patient is in, so (s)he needs to find the patient's room in the tracker. This activity is non-value added and causes a delay in the process.

These three causes (the 2nd, the 3rd, and the 6th most common) that we focus on account for 33.85% of the delay in the process and thus if eliminated, could have a large impact in reducing the flow time.

For the ER patients, Figure 16 shows that the most common cause is that the 'Nurse discusses with other nurses'. In the ER of the St. Catharines Site, each ED nurse has a spot and a computer at the front desk. One nurse is responsible for 4 or 5 patients (rooms) during their shifts. They help each other out and work as a team; for instance, other nurses will watch a nurse's patients while (s)he takes a break. So they communicate with each other a lot, especially when they are working at the front desk. Some of these conversations are necessary but some are not; they can last shorter than one minute or

longer than ten minutes. Since this may potentially create value for the patients or the hospital, this study is not concerned with this cause.

Figure 16: Pareto Chart of Long Flow Time Causes for ER Patient



The second most common one is the 'Nurse answers the patient's concerns and questions'. This usually happens in the patient's room just before or after the phlebotomy process. The hospital advocates patient-centered service and the patients' safety and concerns get the first priority. Thus, the nurse is required to answer and take care of patients' concerns when asked. Thus this not a concern of this study.

The third most common cause is that the 'Patient needs other treatments before or during the process'. The ER patients usually needs multiple tests along with having their blood collected (e.g. measure blood pressure and temperature). Some tests require extra medical equipment for the measurement, and that always takes longer. Based on our observations, not all of these examinations are necessary before the blood collection. If applicable, collecting blood before other examinations could help to reduce the delay in the phlebotomy process.

The fourth most common cause is that the 'Label printing machine is slow'. The delay between the steps, 'Nurse enters information and prints out labels' and 'Nurse gets labels' is caused by the slow label-printing machine. After discussing with hospital staff, we find that the blood test order has to go through several computer systems (including lab systems) before the printing machine can print out the labels. Hence, the nurse will always need to wait for about 20 to 30 seconds to get the labels after (s)he finishes entering blood orders in the computer. As may be expected, the nurse usually will not wait idly, rather, (s)he will attend to other patients (since there are always other patients present) and get the label later. Thus, the nurse will usually get some other work done in the meantime, which often causes this delay to be longer than 20 or 30 seconds.

The fifth common cause is that the 'Nurse goes back to the front desk during the process'; this is undeniably a non-value added activity, and should be eliminated immediately. After the nurse finishes collecting blood, (s)he goes back to the front desk with the specimen and labels, and then labels the specimen at their seats (every nurse has a specific seat in the front desk.) However, this is not appropriate according to the hospital. The nurse should label the specimen right after (s)he collects it at the patient's bedside and then send it to the lab immediately.

These three causes (the 3rd, 4th, and 5th most common) that we focus on account for 33.91% of the total delay. If we focus on these three causes and eliminate them, we can achieve a significant improvement in the process.

Simulation models

Referring to the detailed process maps, simulation models are developed within the Rockwell ARENA (2013) software. Since the UC and ER processes are completely separate (with different resources, different places and different times), there will be two independent models, run simultaneously. It would be possible to combine these into one model, but that would be quite different from how they operate and it is quite unlikely that the hospital will take steps to inter-link these two areas. All activities and delays (interruption, waiting) are modeled. The time of each activity in the process and the delay

between them are obtained from the data collected, and the probability distributions are fitted with the Arena Input Analyzer based on Chi-squared and Kolmogorov-Smirnov statistics. The major activity distributions are listed in Tables 4 and 5.

Note that the distributions used in the model are modified from the fitted distributions, by setting the minimum possible processing times to be the minimum observed in the data we collected. These minimums are quite small, meaning it is very unlikely that these activities can be done any faster than they already are – this was a necessary step for validation.

Table 4: Input Data Distributions for UC Patients

UC Activity	Fitted Distribution*	Mean	Standard Deviation	Distributions Used in the Model
Nurse Enters Information	EXPO(2.26)	2.26	1.84	MX(0.43,EXPO(2.26))
MLA Prepares Items	GAMM(0.138, 5.4)	0.743	0.324	MX(0.1,GAMM(0.138, 5.4))
MLA Collects Blood	EXPO(2.08)	2.08	1.92	MX(0.38,EXPO(2.08))
MLA Labels Specimen	LOGN(0.833, 0.543)	0.831	0.546	MX(0.15,LOGN(0.833, 0.543))
MLA Sends Specimen to the lab	EXPO(0.593)	0.593	0.398	MX(0.2,EXPO(0.593))

*All units are in minutes

Table 5: Input Data Distributions for ER Patients

ER Activity	Fitted Distribution*	Mean	Standard Deviation	Distributions Used in the Model
Nurse Enters Information	GAMM(0.616, 2.97)	1.83	1.63	MX(0.47, GAMM(0.616, 2.97))
Nurse Prepares Items	LOGN(0.973, 0.508)	0.976	0.542	MX(0.43,LOGN(0.973, 0.508))
Nurse Collects Blood	1 + EXPO(3.55)	4.55	4.08	1 + EXPO(3.55)
Nurse Labels Specimen	GAMM(0.558, 2.42)	1.35	0.847	MX(0.1, GAMM(0.558, 2.42))
Nurse Sends Specimen to the lab	GAMM(0.192, 2.42)	0.462	0.323	MX(0.18, LOGN(0.459, 0.237))

*All units are in minutes

The other distribution needed for modeling is the order interval time, but unfortunately it was not possible to collect precise data. The number of orders per hour was recorded exactly, but the precise time of the order being placed was not always observed. This is

because the UC is very busy and always has patients waiting in line. There is only one doctor who takes care of all the UC patients, and it was rather impractical to follow the doctor around asking him/her if and when (s)he orders a blood test. Moreover, when the doctor orders a blood test, (s)he just writes it down on the patient's chart and puts the chart into a 'doctor-order' basket. Even when there was no blood order, the doctor may list other orders on the chart and put it into the basket; therefore it was not always possible to obtain the precise time of a phlebotomy order. When this occurred during data collection, it represented missing data and was not used in the calculation of flow time for that portion of the process.

A similar situation is seen in the ER. Here, the nurse orders blood tests for patients, so (s)he can order the blood test any time after the patient arrives. For instance, a nurse could order a blood test just after (s)he finishes reading the patient's medical history, or decide to do so during or after assessing the patient. Thus, the data does not reflect precise order times, although they were recorded as accurately as possible by communicating and confirming with the nurses. Although order intervals may not have been collected precisely, the number of orders per hour is accurate for both ER and UC patients.

Therefore, instead of fitting an inter-arrival distribution directly from the observed data, the average arrival rate is used to create an exponential distribution that represents the inter-arrival times. As discussed before, the order interval time for the A pod patients is adjusted according to the times in the B pod. Table 6 shows the distributions used for both UC and ER patients.

Table 6: Order Interval

	UC Patient	A Pod ER Patient	B Pod ER Patient
Order Interval	1.65 + EXPO(29)	5 + EXPO(26)	7 + EXPO(36)

Unit: minutes

As discussed in Kelton et al. (2010), the simulation models can be verified by allowing only a single entity to enter the system; and making sure that this entity's logic and the data are correct. Secondly, it is not uncommon to replace some or all model data with

constants. Using these simple and deterministic data inputs, we can predict the process behavior accurately. Consequently, the simulation models were verified by tracing the blood orders and manipulating the input data. In addition, the SIMAN code was reviewed to confirm the model logic.

The models are built to represent the 11 busy hours, from 11 AM to 10 PM. To get a steady average flow time, a 2 hour warm-up period is used. After some pre-tests, we decided to control the half-widths of the performance measure to be no larger than 0.3; this is a high level of precision that is quite sufficient to understand differences between scenarios (in 95% of repeated trials, the sample mean would be reported to be within ± 0.3 minutes). As such, 1000 replications were run, resulting in a maximum half-width of 0.21.

Using the order intervals from Table 6, the simulation models show 48 orders (21 for UC and 37 for ER), which are completed at a 4.36/hour rate, with an average flow time of 28 minutes (30 minutes for UC and 27 for ER). As discussed above, we expect the blood order data collected by our observations to have a lower number of blood orders than those reflected in the hospital's data. Thus, we can conclude that the model is correctly validated.

4.4 Improve

The lean, Six Sigma and simulation techniques are applied to generate potential remedies. Based on the analysis above, we identify a number of suggestions for improvement. Our improvement efforts are focused on reducing the most common causes of delay in the process, as discussed above. As such, the following suggestions focus on changes that can reduce flow time without reducing quality of care.

Suggestion 1: If an ER patient needs to do a blood test, the nurse could collect the blood before other treatments or examinations.

This suggestion requires that the nurses put the blood test as their first priority. It will allow most of the delay between 'Nurse Orders' and 'Nurse Enters Information and Prints

out labels' to be eliminated. According to our observations, this delay accounted for 12.21% of the total flow time and is the third most common cause of delay in the ER.

Suggestion 2: Re-arrange the ER process – An ER nurse could collect the blood before (s)he enters the information and prints out the labels.

As we mentioned before, there are two different procedures used for the ER process. The procedure presented in the Measure stage is recommended by the hospital. However, half of the ER nurses prefer to do it in another way, which is to collect the blood before they enter the information and print out the labels. Because some nurses will assess a patient in the patient's room first, and then decide to do a blood test (or not), collecting blood before entering information may save some traveling time (the time of traveling back to the desk). This procedure is not currently recommended by the hospital, because the lab manager is concerned there will be a potential risk of confusing specimens if two nurses bring back the unlabeled specimens to the front desk at the same time. However, no such errors took place during our data collection (studying the error rate more carefully could be done in a future study). We interviewed the nurses, who explained that they already had labels with patient's name when they were collecting the blood, and they would label the specimen with the patient's name right after collecting it. In this way they eliminated the risk of confusing specimens, and then attached the blood order label once it was printed. Moreover, the nurses consider that both procedures are acceptable and will not result in a significant difference. We therefore suggest re-arranging the process; we will test this in the simulation model later to see if it causes any difference.

Suggestion 3: Re-arrange the UC process – When a UC nurse gets a blood order from the doctor, (s)he could call an MLA before (s)he enters the information and prints out the labels.

Normally, a UC nurse enters the information into the computer, and then calls an MLA. Of course this avoids problems associated with the nurse forgetting to enter the information afterwards, but, on the other hand, it always takes time for the MLA to come to the UC and the nurse always needs to wait. Calling the MLA first allows the nurse to

enter the information while (s)he is waiting. From the entire process standpoint, the nurse can save some time by entering the information during the wait, and it is reasonable to assume that the nurse would only forget to enter the order in very extreme circumstances (e.g., a true emergency for some other patient).

Suggestion 4: Add a full-time MLA to collect blood from both UC and ER patients

As discussed before, the 'Nurse calls the MLA' in the UC phlebotomy process is a non-value added but necessary activity. It should be minimized or better yet, completely eliminated in the future. Adding a full-time MLA allows completely eliminating this activity and the waiting time that it causes. This suggestion also addresses the 3rd most common cause of delay (Nurse waits for a MLA) for the UC patients. Moreover, for ER patients, this suggestion decreases the workload of ER nurses and speeds up the phlebotomy process.

Suggestion 5: Maintain the float nurse in the UC, but slightly adjust the job description by setting blood collection as the first priority

Currently in the ED of the St. Catharines Site, they are carrying out a trial project by having a float nurse to help with the patient flow. The purpose is to increase the number of patients served in a day. If this trial is successful, the hospital will implement this project permanently; but if not, they will just call it off. This float nurse's responsibility is the same as other nurses, but (s)he does not have a fixed position. (S)he floats everywhere to help out. However, carrying out a blood order is not the first priority for the float nurse in this trial project. If the hospital suggests that the float nurse take care of all the blood orders in the UC, it can not only reduce the flow time of the UC phlebotomy process, but also save the time and cost of calling a MLA to the UC – a MLA would no longer be required, not even in the busiest hours. This suggestion solves the 2nd, 3rd, and 5th most common causes of delay altogether. This, of course, assumes that phlebotomy would become the highest priority for this nurse, above other tasks. S(he) would need to be called or notified whenever a blood order is placed so s(he) could quickly finish his/her current task and then go draw the blood.

Using a float nurse allows the nurse to do other nursing jobs when (s)he is not doing phlebotomy; and therefore has some advantages over adding a full-time MLA (Suggestion 4), because a full time MLA would have idle time when not doing phlebotomy. Suggestion 5 could also help to reduce the workload of UC nurses while adding a MLA will not.

Suggestion 6: For ER patients, an ER nurse could label the specimen at the bedside and send it to the lab right after that.

First of all, it is the hospital's suggestion that a nurse could label the specimen at the patient's bedside right after (s)he finishes collecting the blood. During our observation, we witnessed that most of the nurses labeled the specimen after going back to the front desk. This is the 5th cause of delay for ER patients; it is unnecessary movement.

Suggestion 7: Improve the speed of electronic communications (reduce the label printing time)

The issue of the label printing requiring 20-30 seconds and the related repercussions have been discussed earlier. It is the 4th most common cause of delay in the ER process. If the hospital can replace the current system with more advanced technology, the time lapse due to electronic communications can be minimized, e.g., most of the delay between 'Nurse enters information' and 'Nurse gets the labels' can be eliminated.

Suggestion 8: A UC nurse could write down the patient's room number on the labels for the MLA.

A few delays between 'MLA gets labels' and '(s)he begins preparing items' are because the MLA does not know which room the patient is in. This is the 5th most common cause of delay in the UC process. If a UC nurse writes the patient's room number on the labels, the MLA can directly go to the patient and collect blood. This way, time is not wasted in finding the patient's room from the tracker.

Suggestion 9: If a patient needs to do a blood test, a UC nurse could tell the patient not to leave the room until the blood has been collected.

There are several incidences during our observations that a patient (who needs blood to be drawn) is seen to just leave the room for other purposes (the 12th most common cause of delay). This makes the MLA wait idly in the UC, which causes process delays, also increasing the waiting time of the next patient who needs to get blood drawn by the MLA.

Suggestion 10: The hospital could modify their policy to require MLAs to answer calls except when they are collecting blood (requiring them to return calls after the process is done).

Answering phone calls during the process is identified as the 2nd most common cause of delay in the UC process. MLAs have to have a cellphone and a cart (with necessary items) with them at all times. They handle blood orders everywhere in the hospital. This is why they need to answer phone calls, as blood orders always come in over the phone. However, when a MLA is doing the phlebotomy process, it is not appropriate to answer the phone right away. As suggested by the lab manager, the call can be returned later – after finishing the process. This can be helpful in reducing delays within the process.

Suggestion 11: Refill necessary items regularly

For ER patients, the phlebotomy process can get delayed if an ER nurse cannot find all the necessary items in the patient's room. This is the 11th most common cause of delay in the ER process. Getting every necessary resource ready is a requirement of lean principles. It helps the process flow without interruptions when a patient requires it. This can be applied to MLA carts as well (restocking them in time). Keeping all necessary items available is one step towards avoiding unnecessary process delays.

4.4.1 Simulation modeling

Due to the data limitations and the challenges in modeling the impact of some suggestions accurately, not all the suggestions will be tested with the simulation model. The suggestions are linked to the causes of delay, where delay is essentially defined as the time gap between consecutive steps in the process. Unfortunately, for some of the causes it is difficult to determine quantitatively how much delay that particular cause creates. However, Suggestions 1 to 7 are associated with causes for which this is possible.

These seven suggestions, along with some reasonable combinations of among them, can be simulated.

The base models, denoted Case O (Original), represent the current state of the ED and are developed from the value stream maps from the Measure stage. The blood order interval times and the times of each activity demonstrated in the Analyze stage are used in generating a Case O for the ER patients, and a separate Case O for the UC patients. (In addition to the two initial Case O's, there will be a Case O for each of the different demand levels, further explained below).

Case A, modelling Suggestion 1, is to adjust the delay between 'Nurse orders' and 'Nurse enters information' from '2+EXPO(205)' seconds to 5 seconds. This '5 seconds' is an average estimation, based on the average distance from the front desk to the patient's room (recall that the front desk is central, very close to all patient rooms in the area). It is not reasonable to reduce this to zero, so we allow 5 seconds for traveling time. If the hospital follows Suggestion 1, the flow time could be reduced.

Case B (Suggestion 2) is to re-arrange the ER procedures. It is to simulate the collection of blood before an ER nurse enters the patient information. As discussed before, the hospital does not support this sequence, but about half of all the nurses prefer to use it. We therefore model this for comparison and discussion.

Case C is to re-arrange the UC procedures (Suggestion 3). The idea is to switch the steps 'Nurse calls the MLA' and 'Nurse enters the information and prints out the labels'. By doing this, the time to enter information can be eliminated from the phlebotomy process since it will occur while waiting for the MLA.

Suggestion 4 is represented by Case D, which recommends adding a full-time MLA in the ED. The lab manager, the actual proponent of this is suggestion, wants to know how much time he can save if he puts a full-time MLA in the ED and has the MLA take care of all blood orders. This reduces the need for ER nurses to draw blood and also allows for the calling time and the waiting for the MLA in the UC to be completely eliminated.

According to Suggestion 5, Case E will test the situation when a float nurse handles all the blood orders in the UC (and does so as first priority). It will show how the flow time of UC phlebotomy will change. It means that a UC nurse will not need to call and wait for an MLA. It eliminates the non-value added but necessary activity of the nurse calling the MLA and the delays it causes.

Case F will test by how much flow time the phlebotomy process can be reduced if the hospital implements Suggestion 6. We suggest the nurse labels the specimen right after (s)he finishes collecting the blood at the patient's bedside. For this, we change the delay between 'Nurse Collects Blood' and 'Labels the Specimen', which is '6+EXPO(191)', to 0 seconds. This suggestion can completely remove the delay between the 'Nurse collects blood' and 'Nurse labels specimen' in the ER process.

Case G is to simulate an improvement in the speed of electronic communications (Suggestion 7). Considering the traveling time, we adjust the delay between 'Nurse enters information' and 'Nurse gets labels' from '5 + WEIB(82, 0.757)' to 5 seconds.

Some of the above suggestions can be implemented simultaneously. Of the seven cases, two involve adding extra staff (Case D & E), and one is about a technical problem which may need extra time and effort to solve (Case G), while the rest (Case A, B, C & F) only involve adjustments of the procedures in the processes. Therefore, we only focus on the combinations that are possible and that can be implemented soon.

Two of the combinations that will be tested are Cases A & B (denoted as Case AB), and Cases A & F (denoted as Case AF). Another combination that may add great improvement to the flow time is the combination of Case A and Case D. Note that Case A (Suggestion 1) is concerned with the adjustment of the ER process only, whereas Case D links the UC and ER processes by sharing a MLA. Hence, this combination basically is to test the combinational effect on the ER process. This will be termed as Case AD.

We should note that there are no cases that can be combined realistically with Case E, since it only affects the UC process. Case C is to switch the information entering step and calling step, the latter being absent in Case E. Obviously, since Case D involves a full-time

MLA and Case E involves a float nurse with blood collection as her first priority, the two cannot be combined. Another impossible combination is cases B and F. In the rearrangement of the ER process, as Case B suggests, the nurse has to go back to the front desk to enter the information into the computer after (s)he finishes collecting the blood. Case F provides a contradicting solution where the nurse does not need to go back to the front desk after (s)he finishes collecting the blood.

Lastly, considering two lean principles, which are Flow and Perfection, all waste within a process should be eliminated to create only value added flow towards the patient. Also, this is the goal we want to achieve finally, towards Perfection. Thus, this last case marked as Case P (Perfect) is to remove all the delays within the processes.

To summarize:

- Case O: Base Models
- Case A: Remove the delay between 'Nurse orders' and 'Nurse enters information' (Suggestion 1) (Only ER)
- Case B: Re-arrange the ER procedures (Suggestion 2) (Only ER)
- Case C: Re-arrange the UC procedures (Suggestion 3) (Only UC)
- Case D: Add a full-time MLA (Suggestion 4) (UC & ER)
- Case E: Add a float nurse in the UC (Suggestion 5) (Only UC)
- Case F: Remove the delay between 'Nurse labels specimen' and 'Nurse sends specimen to the lab' (Suggestion 6) (Only ER)
- Case G: Remove the delay between 'Nurse enters information' and 'Nurse gets Labels' (Suggestion 7) (Only ER)
- Case AB: Combination of Case A and Case B (Only ER)
- Case AF: Combination of Case A and Case F (Only ER)
- Case AD: Combination of Case A and Case D (UC & ER)
- Case P: Remove all delays (Perfect process) (UC & ER)

In addition, an experimental factor – the blood order interval time, or system load – is tested. In the future, as the patient number increases in the ED of the St. Catharines Site, the blood orders could increase as well. This experimental factor, which we call the Demand Level, is used to predict how demand may increase in the future and how it will impact the various suggestions.

Average results from 1000 replications for all Cases are provided in Table 7. As discussed before, the UC and ER processes are two independent processes. Blank cells occur when the corresponding case does not impact that process.

Table 7: Simulation Results – Mean (95% confidence interval)

Average Flow Time	Current Demand Level		Increase Demand by 10%		Increase Demand by 20%	
	UC	ER	UC	ER	UC	ER
Case O (UC&ER)	30.53 (+/- 0.18)	27.73 (+/- 0.12)	30.60 (+/- 0.17)	27.85 (+/- 0.12)	30.65 (+/- 0.16)	27.83 (+/- 0.11)
Case A (ER)		24.24 (+/- 0.12)		24.29 (+/- 0.11)		24.32 (+/- 0.10)
Case B (ER)		24.93 (+/- 0.09)		25.00 (+/- 0.09)		24.92 (+/- 0.09)
Case C (UC)	26.11 (+/- 0.17)		26.24 (+/- 0.17)		26.34 (+/- 0.17)	
Case D (UC&ER)	21.66 (+/- 0.17)	19.71 (+/- 0.12)	22.59 (+/- 0.19)	20.73 (+/- 0.14)	23.82 (+/- 0.22)	21.81 (+/- 0.17)
Case E (UC)	22.18 (+/- 0.15)		22.58 (+/- 0.16)		22.97 (+/- 0.16)	
Case F (ER)		24.39 (+/- 0.12)		24.47 (+/- 0.11)		24.40 (+/- 0.10)
Case G (ER)		26.08 (+/- 0.12)		26.05 (+/- 0.11)		26.12 (+/- 0.11)
Case AB (ER)		21.20 (+/- 0.08)		21.17 (+/- 0.08)		21.17 (+/- 0.08)
Case AF (ER)		20.99 (+/- 0.10)		20.97 (+/- 0.10)		21.04 (+/- 0.10)
Case AD (UC&ER)	21.37 (+/- 0.16)	16.18 (+/- 0.11)	22.47 (+/- 0.20)	17.08 (+/- 0.14)	23.48 (+/- 0.22)	18.13 (+/- 0.19)
Case P (UC&ER)	6.85 (+/- 0.05)	9.15 (+/- 0.04)	6.97 (+/- 0.05)	9.09 (+/- 0.04)	6.96 (+/- 0.05)	9.14 (+/- 0.04)

Unit: minutes

4.4.2 Statistical Results

An ANOVA test in SPSS is utilized to test the significance of the cases and demand levels. The results indicate that all the cases are significantly different from their base models (Case O). It means the suggestions tested in the simulation can each cause a statistically significant improvement in the flow time. Because there are different suggestions (improvements) for the UC and ER processes, the next section will discuss the results separately.

UC patients

As explained above, six cases (O, C, D, E, AD, and P) and their three demand levels are tested for the UC patients using ANOVA. Table 8 summarizes the results for all UC cases and levels. It indicates that Case, Demand Level and their interaction all have a significant effect on the flow time.

Table 8: UC ANOVA Result

Tests of Between-Subjects Effects						
Dependent Variable: Flow Time						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	947118.764[a]	17	55712.868	7971.736	.000	.883
Intercept	8636407.470	1	8636407.470	1235749.765	.000	.986
Case	942493.720	5	188498.744	26971.548	.000	.882
Demand Level	2393.876	2	1196.938	171.265	.000	.019
Case * Demand Level	2231.168	10	223.117	31.925	.000	.017
Error	125672.595	17982	6.989			
Total	9709198.828	18000				
Corrected Total	1072791.359	17999				
a. R Squared = .883 (Adjusted R Squared = .883)						

To further investigate each case's effect on the flow time, a Post Hoc Test (Tukey) was conducted. Table 9 shows the Homogeneous Subsets of UC patients, a result of the Tukey analysis.

Table 9: UC Homogeneous Subsets

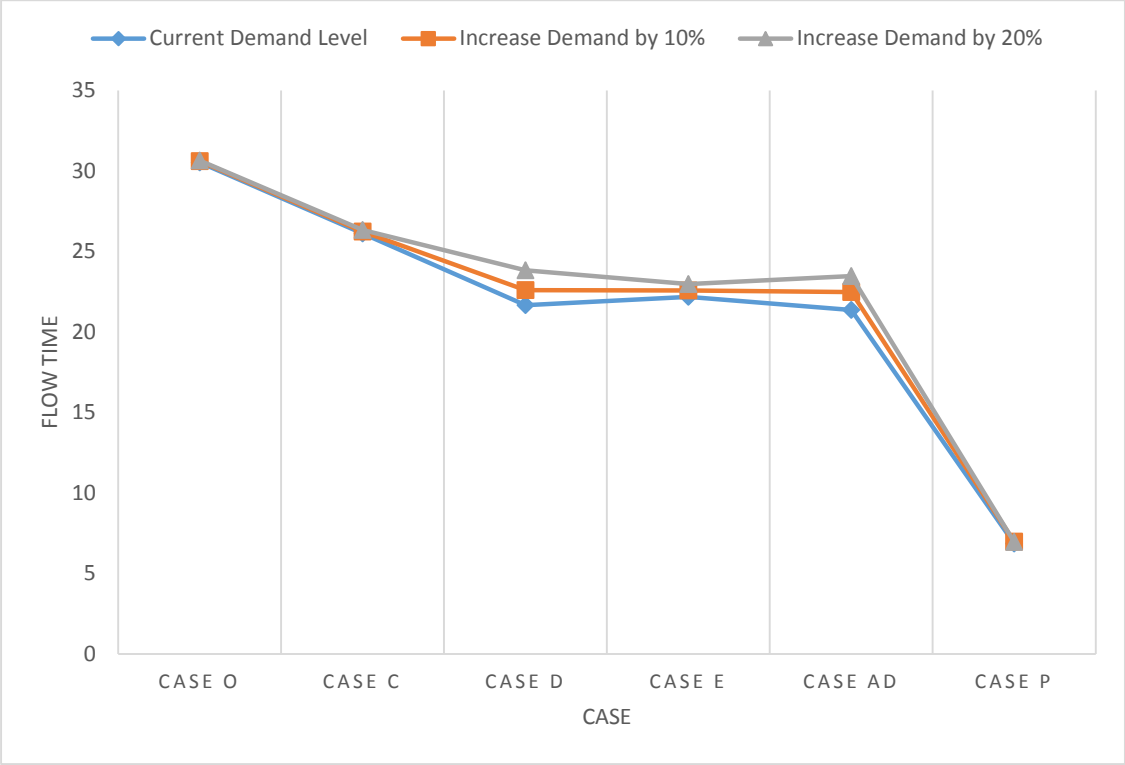
UC Flow Time						
Tukey HSD[a,b]						
Case	N	Subset				
		1	2	3	4	5
P	3000	6.92				
E	3000		22.57			
AD	3000			22.80		
D	3000			22.86		
C	3000				25.96	
O	3000					30.32
Sig.		1.00	1.00	.92	1.00	1.00
Means for groups in homogeneous subsets are displayed. Based on observed means. The error term is Mean Square(Error) = 6.989.						
a. Uses Harmonic Mean Sample Size = 3000.000.						
b. Alpha = .05.						

We find that all cases are significantly different from Case O (base case). Case D and Case AD have no significant difference from each other. This is because Case AD is the combination of Case A and Case D, and Case A does not have an effect on the UC process. We will not discuss Case AD in the UC section as it will be redundant.

Also, a Multiple Comparisons test (see Appendix A) supports the results from the Homogeneous Subsets analysis. All cases show significant difference from each other, except Cases D and AD.

To visualize the interaction, the results are charted in Figure 17. We find that in Case O, Case C and Case P, the flow times are almost the same for all three demand levels. Case D and Case E show a difference for the three demand levels.

Figure 17: UC Average Flow Time Diagram



Pairwise comparisons are used to further explore the effect of different demand levels in each case (Appendix B). Consistent with Figure 17, we find that only Case D and Case E show a significant difference at different demand levels. This suggests that their effect on flow time is modified by the Demand Level, which is also the cause of the significant interaction. In these two cases, there is a small amount of waiting time that a patient needs to spend waiting for a MLA or a float nurse to collect their blood. As the demand level increases, the waiting time increases, which decreases the reduction of flow time created by Case D or Case E. We should note that in other cases (Case O, C, and P) as well, there is a small amount of waiting time (e.g. 0.5 minutes). However, even with a 20% increase in demand, these waiting times do not see a significant difference. On the other hand, it should be noted that if demand doubles in the future, waiting time may cause problems. Thus, if demand increases substantially, attention will need to be paid to the waiting time and different models will be required.

As we can see from the Homogeneous Subsets analysis (Table 9), Case E provides a sizeable improvement – a 7.75 minute reduction in flow time. When making this

suggestion, we are aware that the salary range of a registered nurse is $30.17 - $43.61 per hour. To justify this cost, we suggest that the job description of the float nurse include blood orders as the first priority. To some extent, the float nurse may help to release the workload pressure of the UC nurses as well as improve the patients' experience. As mentioned earlier, the hospital already has a float nurse in the UC, as part of a trial project in the ED of the St. Catharines Site. The only adjustment necessary (for Case E) is to ask the float nurse to put blood collection as the first priority.

The second best case is Case D, which is to add a full-time MLA to do the blood collection for UC and ER patients. The salary range for a full-time MLA is $24.18 - $27.88 per hour, which is less than that for a nurse, making a full-time MLA more affordable. This suggestion completely eliminates the calling procedure within the UC process and a large amount of waiting time caused by that. This 7.46 minute reduction from the phlebotomy flow time might help reduce the total time of the patient stay in the UC. The patient can get the blood test result more quickly, get a diagnosis and treatment, and then leave. It saves the patient's time and also increases UC efficiency and capacity. However, with this case there is still a small amount of waiting time involved. Because only one MLA will work for both UC and ER patients, this increases the chance that orders would be made at the same time, and if so then some patients may need to wait until the previous one is done. As the demand level increases in the future, the waiting time could be longer, reducing the impact of this suggestion.

Case C suggests calling an MLA first so that the nurse can enter information while waiting for the MLA. From the cost perspective, re-arranging the procedures is relatively easy and would not result in extra expense. However, calling an MLA before a nurse enters the information and prints out the labels has a slight risk of the nurse forgetting to enter the information and print the labels. Then, the MLA would have to wait if labels are not ready. Although this hasn't happened during our observation, we recommend Case C to be implemented with a safeguard or way to help nurses remember to enter the order.

In short, based on the current situation in the ED of the St. Catharines Site, we first suggest implementing Case E for UC patients. Although the wage of a nurse is higher than for an MLA, a nurse is preferred over an MLA as (s)he will be more productive, doing other tasks when no blood draws are needed. In addition, the hospital already has a float nurse assigned for busy hours. If, for some reason, adding a float nurse is not possible, we then recommend considering adding an extra staff member—a full-time MLA, who can replace the float nurse (Case D). Lastly, if neither of these options are possible, we recommend Case C.

ER patients

As shown in Table 7, ten cases for ER patients (Case O, A, B, D, F, G, AB, AF, AD, and P), as well as their three demand levels, are tested. Table 10 shows the ANOVA results.

Table 10: ER ANOVA Result

Tests of Between-Subjects Effects						
Dependent Variable: Flow Time						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	761605[a]	29	26262	8260	0	.88
Intercept	13985764	1	13985764	4399223	0	.99
Case	757781	9	84197	26484	0	.88
Demand Level	829	2	414.67	130	0	.00
Case * Demand Level	2994	18	166	52	0	.03
Error	95278	29970	3			
Total	14842648	30000				
Corrected Total	856884	29999				
a. R Squared = .889 (Adjusted R Squared = .889)						

Table 10 shows that both the Case and the Demand Level as well as their interaction have a significant influence on the flow time. Similar to the analysis for the UC patients, we apply a Post Hoc Test (Tukey) to reveal the significance between cases and demand levels (Table 11).

The Homogeneous Subsets of ER patients (Table 11) shows that all nine cases are significantly different from Case O, which means that each of the suggestions (and their combinations) for the ER process result in a significant improvement in the flow time. This

table also indicates that there is no significant difference between Case A and Case F, between Case AB and Case D, and between Case AF and Case D. Moreover, Multiple Comparisons between cases (Appendix C) also support these results.

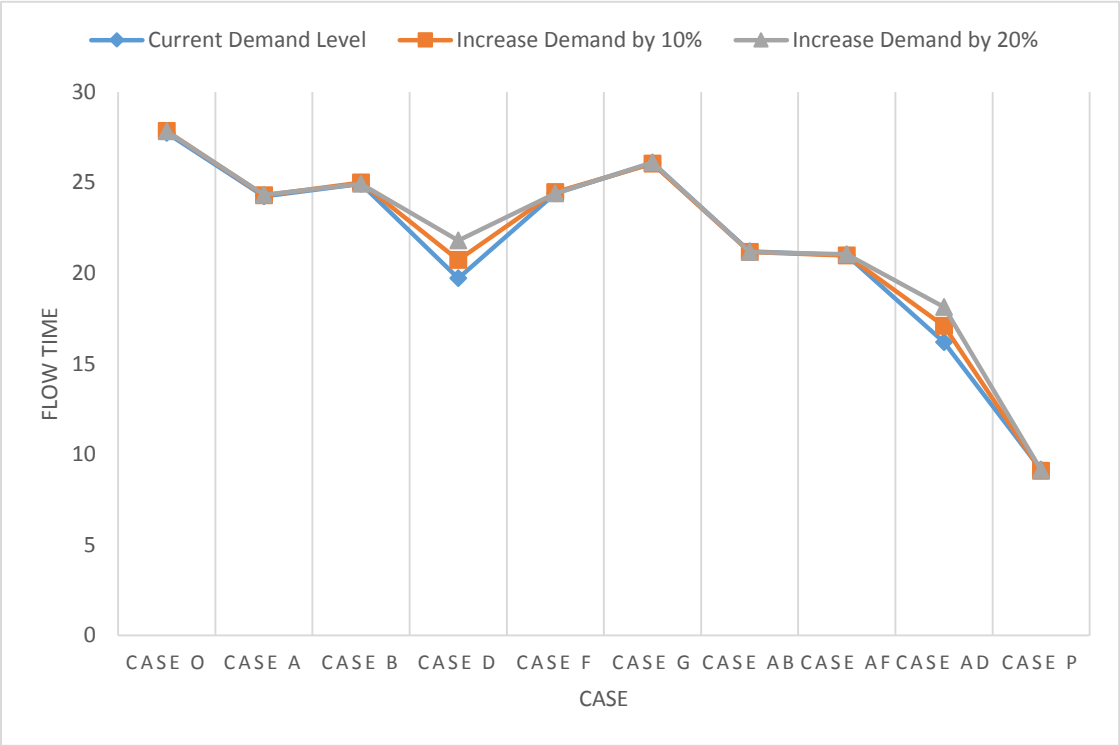
Table 11: ER Homogeneous Subsets

Flow Time									
Tukey HSD[a,b]									
Case	N	Subset							
		1	2	3	4	5	6	7	8
P	3000	9.11							
AD	3000		17.37						
AF	3000			20.84					
D	3000			20.95	20.95				
AB	3000				21.06				
A	3000					24.10			
F	3000					24.20			
B	3000						24.83		
G	3000							25.88	
O	3000								27.57
Sig.		1.000	1.000	.298	.368	.462	1.000	1.000	1.000
Means for groups in homogeneous subsets are displayed. Based on observed means. The error term is Mean Square (Error) = 3.179.									
a. Uses Harmonic Mean Sample Size = 3000.000.									
b. Alpha = .05.									

To investigate the effect of Demand Level as well as the interaction, the average flow time of each case and their three demand levels are plotted in Figure 18. It shows that except Case D and Case AD, there is little or no difference for different demand levels. In Case D and Case AD, as the demand increases, the flow time decreases less. Also, the interaction effect seems to be created by Case D and Case AD, which is verified by Pairwise Comparisons tests (Appendix C). It compares the three demand levels within each case. The results show that only Case D and Case AD are significantly different at different demand levels. Other cases have no significant difference in the three demand levels. The reason is similar to what we explained in the UC section before. It is because there is waiting time in Case D and Case AD, but not in Case O, A, B, F, G, AB, AF and P. In these two cases, all the patients share one MLA for their blood collection and they may need to

spend a small amount of time waiting for the MLA. Hence, as the demand level increases, the waiting time increases, which modifies the reduction of flow time.

Figure 18: ER Average Flow Time



Additionally, from Table 11, we find that Case AD provides the most improvement. It reduces the flow time to 17.37 minutes (10.2 minute reduction). Case D individually reduces flow time 6.62 minutes and Case A alone reduces it 3.47 minutes. So Case AD is the combined improvement from Case A and Case D, and these two cases will be discussed later.

The second best are Case AF and Case D. Case AF provides a 6.73 minute reduction in flow time. The combined improvement from Case A (3.47 minutes) and Case F (3.37 minutes) can be obtained at the same time, and will be discussed further later. Case D reduces the ER nurses work slightly, by adding a full-time MLA. A full-time MLA speeds up the process not only by reducing the delays but also by accelerating the value added activities (e.g. preparation and collection). This change will allow the ER nurse to focus more on patient experience in the ED, while letting the MLA concentrate solely on the phlebotomy process. This may also reduce chances of 'distraction' (delay) in the process. For example, when

an ER nurse undertakes the process, (s)he may face patient questions, which they need to answer, since they are more familiar with the patients' conditions. MLAs, on the other hand, will be less familiar and less qualified regarding the patient's situation, and therefore may communicate less with the patient during the process – and can thus save some flow time.

As explained in the UC section, in Case D, multiple orders may come in at the same time, causing some patients to wait for the MLA. However, the simulation result shows MLA utilization, at the current demand level, to be 0.59. Therefore, we do not recommend adding more MLAs at this point due to the high idle time, but may be useful if demand increases in the future.

The following case is Case AB, which reduces the flow time by 6.51 minutes; Case A alone accounts for a reduction of 3.47 minutes, while Case B alone reduces the flow time by 2.74 minutes.

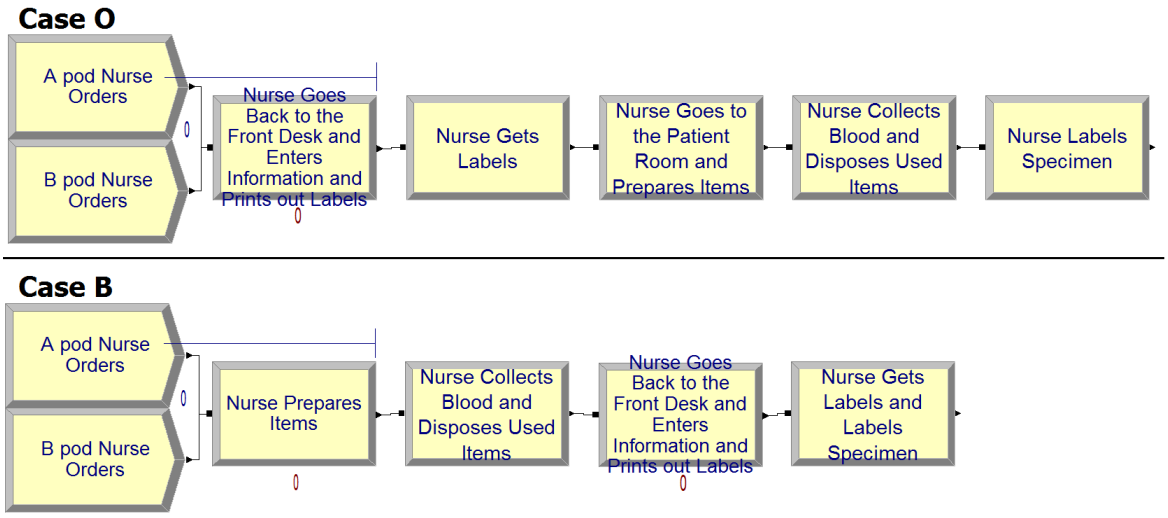
Interestingly, Case AF is not significantly different from Case D, and Case D is not significantly different from Case AB, but Case AF is significantly different from Case AB. However, the difference between Case AF and Case AB is only 0.24 minutes. The hospital may consider this an insignificant difference in practice; after all, adjusting procedures (Case AF or Case AB) may not yield an improvement that is practically different from adding an extra staff member (Case D).

Table 11 also indicates that there is no significant difference between Case A and Case F (they reduce the flow time by 3.47 and 3.37 minutes, respectively). As explained above, this is because the delays they alleviate are almost the same. Due to the similar nature of delays eliminated by Case A and Case F, they show no significant difference on the effect of flow time.

Case B is to re-arrange the ER process where an ER nurse collects the blood before (s)he enters information and prints out labels. In the ED of the St. Catharines Site, most of the ER nurses assess the patients in their rooms after they arrive. Then, the nurse can decide whether to do a blood test right away while still in the patient's room. In Case B, the nurse

does not need to leave the patient to enter information and print out labels. Instead, after collecting blood (s)he carries the specimen back to the front desk, enters information and prints out labels. After that, (s)he labels the specimen and sends it to the lab (the difference in procedures is shown in Figure 19).

Figure 19: Partial Flow Chart for Case O and Case B



Although the hospital does not recommend Case B (as mentioned before), it seems to save some travel time; simulation results show significant improvement due to Case B. However, in their informal interviews with us, some nurses admit that they would rather not collect blood without labels in hand. So we suggest leaving it for the ER nurses to decide which procedure is more efficient and applicable for them.

Case G is to improve the speed of electronic communications. If the hospital can reduce the time the system needs for the blood order to go through to the printer - reducing the label printing time to 5 seconds, then the ER nurses could get their labels immediately, which would reduce the flow time for the phlebotomy process by 1.69 minutes.

To summarize, Case AD is the best case for ER patients, but it requires adding an additional staff member and may not get funding approval from the hospital. This case is also the second best case for UC patients. The best case for UC patients is Case E, which involves a float nurse prioritizing blood collection. The hospital already has a float nurse, so this change will require no extra staff and no extra cost. So for the ER patients, we recommend

implementing Case AF first. Compared with Case AD, Case AF only involves changing procedures, but still yields significant improvement for the flow time. As maintaining a float nurse will cost more than adding a full-time MLA, we consider Case AD to be the best case for both processes, if the hospital decides to stop the float nurse project. Otherwise, we would recommend Case E for the UC process and Case AF for the ER process. Lastly, we should note that except Case AD and Case D, which affect both UC and ER patients, all other cases are independent and can be implemented separately for the UC and the ER processes.

4.4.3 Implementation (to be carried out by the hospital in the future)

As all the suggestions are supported by the statistical results, it can be concluded that all the suggestions bring significant improvements to the flow time. To implement the suggestions, it is necessary to have a reasonable implementation plan.

According to Six Sigma and lean, some trial tests are suggested before transforming the suggestions into regular operations. For this particular phlebotomy process in the ED of the St. Catharines Site, the busy hours are from 11 AM to 10 PM. The busiest day is Monday (mentioned previously in the Measure stage). In order to reduce the time required to run the trial (to get more observations in a short period) and to test it during the highest demand period, we recommend doing it during the busy hours on a Monday, especially when considering adding a full-time MLA. It may not be worthwhile to add a full-time MLA in the non-busy hours, since then the full potential of a full-time MLA may not be accurately gauged. Moreover, recall that there is not a queue in the current phlebotomy process, so each instance of the process should be observable independently from other instances even during the busier times.

We presented our findings to the hospital staff. They are reviewing the findings and attempting to determine which options will work best. It is apparent they are thinking about the issues, because they have already addressed one issue. In order to reduce problems with lack of materials, they have already modified the schedule for the inventory replenishment employees, having at least one working 24 hours a day, 7 days

a week. This modification ensures the hospital has inventory replenishment services throughout the day and night.

4.5 Control

This is the final stage of Six Sigma; however, it will not be illustrated in detail, because this stage will likely be carried out by hospital staff after they implement the improvements. We will only provide some general suggestions that may help the hospital control the process and maintain the gain from the improvements.

In this stage, the last lean principle, which is Perfection, will be applied. Pursuing perfection means zero defects and a hundred percent customer satisfaction. Even though it is difficult, it is always good to strive for that. To achieve this goal, we need to keep the improved process under control.

Control charts are the most common tools that are utilized in the lean-Six Sigma Control stage. To create a control chart, specifications need to be determined by calculating the mean and standard deviation of performance measurement (flow time). Staff and project members can discuss the sigma level of the process in meetings.

Next, managers or front-line staff need to monitor the process for unusual variations. According to Perfection, there is no end to reducing waste, cost and mistakes while performing a process. The control charts are used to record how well the process works and whether it is under control. If the process is out of control, the process should be investigated and adjustments may be necessary. Simulation models can be continuously modified for analysis of the adjusted process.

In addition, any change and progress should be documented and be transparent to all staff members. Regular meetings and visual boards at the workplace are helpful in communicating and controlling improvements.

5. Generalizability of the Methodology

The initial purpose of this thesis was to understand and improve the phlebotomy process in the St Catharines hospital by using lean, Six Sigma and simulation knowledge and tools. The five classic Six Sigma steps (DMAIC) were used as the major framework in this study. Five lean principles and the simulation modeling steps were integrated within the DMAIC framework. Following this framework, we were able to plan and proceed with this study in an efficient and effective way. The framework was adjusted and improved as the study progressed; the final result is provided in Table 12.

From the results and experience we gained from the phlebotomy process study, we now understand that these three methodologies are not only suitable as a combined methodology, but can provide better outcomes when used together. We therefore made an effort to combine them into a framework that can benefit other processes. Based on Table 12, Table 13 was developed to provide a broad structured framework for combining Six Sigma, lean and simulation for other health care improvement projects.

This framework can be particularly useful for problem-solving and continuous improvement in existing processes (as opposed to new process design). (As mentioned, if the project is for a new process design, the DMADV method should be used.) Second, the improvement project which suits this framework can have multiple goals (e.g., interests of different stakeholders, time-based objectives, cost-based objectives). Six Sigma and simulation both have the ability to handle multiple performance measures at the same time. Third, if a project involves improving a process that has variability and interactions between multiple resources, it is recommended to use this framework, because simulation is good at dealing with process variability and complexity. Fourth, when an improvement project needs to compare different scenarios and it is difficult to perform a trial run with the real system, it can benefit from using this framework. For instance, a different process observed during this study that could benefit from this framework is the registration process in the ED of the St. Catharines Site. Other health care processes that

could benefit are be the registration processes in a doctor's office or at specialty clinics, porter processes in hospitals, and laboratory processes.

Considering the diversity of various health care processes, and accounting for a greater variety of projects, more steps within DMAIC are added in Table 13 (compared to Table 12). The framework in Table 13 aims to provide a broad guideline on how to use lean, Six Sigma and simulation together. It shows structured procedures, essential principles, various tools, and an efficient way of combining the three methodologies. By following this framework, potential improvement can be achieved and significant gain can be realized.

It is fine to skip a few of the steps in Table 13 if they do not apply to specific situations. For instance, in the third step of Define and the fourth step of Analyze, we suggest using historical data to define a problem or validate the model. However, it is common for many organizations not to have historical data. For such cases, we suggest skipping these steps, and do the best to define the problem in other ways (e.g., trial observations).

Table 12: The structured framework of Six Sigma, lean and simulation for the phlebotomy project in the ED of St. Catharines Site

DMAIC	STEP	LEAN PRINCIPLE	TOOLS	SIMULATION STEP	OUTCOME	Note
Define	Describe problem symptoms	Value		Understand the process	Awareness of the process problems	It was the lab manager that noticed the process had an unreasonable long flow time.
	Observe/get involved in the process		Observations, Interviews	Understand the process	Preliminary process maps	Preliminary process maps were built based on a few observations.
	Collect relevant historical data		Microsoft Excel	Understand the process	Process characters	The average flow time in the hospital's record was 30 minutes, and this is quite long compared to other hospitals, according to the lab manager.
	Define the performance measurement	Value	Meetings	Be clear about the goals	Performance measurement	To account for both the patients' and hospital's point of view, the flow time was determined as the performance measurement to evaluate the process.
	Create a project charter	Value	Meetings	Be clear about the goals	Project statement, scope, performance measurements, goals	The process problems, project goals, scope, agenda, and etc. were summarized in a project charter (Table 1), which were decided by the lab manager, ED manager and QI advisors in the meetings.
Measure	Create detailed process maps	Value stream map (VSM)	Observations, Interviews	Formulate the model representation	Detailed process maps	Detailed process maps were built by extending the preliminary process maps.
	Define data samples size and collection plan		Meetings		Data collection plan	Contact the lab and ED managers for available days for data collection.

DMAIC	STEP	LEAN PRINCIPLE	TOOLS	SIMULATION STEP	OUTCOME	Note
Measure (cont.)	Collect relevant process data	VSM	Observations, Interviews, Microsoft Excel	Time study and observation	Observational data	First discussed data collection with the nurses and MLAs who were involved in the process. Collected time stamp data for over 100 hours.
	Build value stream maps and measure different activities within the process	VSM	Microsoft PowerPoint, Arena		Value stream maps	Value stream maps and the corresponding tables were used to classify and summarize the activities and their time.
	Validate the value stream maps	VSM	Microsoft Excel		Validated value stream maps	The average flow time we collected was validated by comparing with the historical data.
	Translate the VSM into modeling software		Arena	Build the simulation model	Value stream maps in Simulation	Complete and detailed value stream maps in simulation represented the current stage of the processes (base model).
Analyze	Analyze historical and observational data		Microsoft Excel		Process pattern and tendency	The order frequency from hospital's data was analyzed and used to validate the simulation model and facilitate the Improve stage later.
	Determine causes of problems and gather data on the causes (quantify the causes)	Flow	Observation, Meetings, Pareto Chart Cause & effect diagram, Microsoft Excel		Causes of the problem and their frequency	We used the cause-effect diagram and Pareto chart to show the frequency of the causes of delay. Later suggestions were generated based on these causes.

DMAIC	STEP	LEAN PRINCIPLE	TOOLS	SIMULATION STEP	OUTCOME	Note
Analyze (cont.)	Determine the best fit distributions of input data and input into the simulation model		Input analyzer, Arena	Input the data distributions into the model	Statistical data, Model of current stage	We cleaned our data and removed some outliers before using the Arena Input analyzer to fit the distributions.
	Verify and validate the simulation model		Arena, Microsoft Excel	Verification and validation	A representative model of the current stage	We verified our models by tracing the blood orders and manipulating input data. For validation, we compared our order interval time and average flow time with the hospital historical data.
	Document the current flow time		Arena, Microsoft Excel	Run the model	Flow time of current process	The flow time of the current hospital process was generated by running the simulation models.
Improve	Develop potential suggestions	Flow Pull	Meetings, Arena		Potential suggestions	We developed 11 suggestions based on the causes of delay.
	Model different suggestions in simulation		Arena	Design the experiments and run the different suggestions	Potential flow time	Seven suggestions and their reasonable combinations were modeled in simulation.
	Evaluate different outcomes		ANOVA test/SPSS	Analyze the results Get insight	Significant results (significant suggestions)	The simulation models and ANOVA test results supported and explained the differences to expect between the suggestions.
	Implementation (by hospital staff)		*Microsoft Excel*		*Implementation plans*	*We gave some suggestions for implementation based on the analysis of historical data.*

DMAIC	STEP	LEAN PRINCIPLE	TOOLS	SIMULATION STEP	OUTCOME	Note
Control	*Determine the control limit(sigma levels)*	*Perfection*	*Meetings*		*Specifications*	*By calculating the mean and standard deviation of a performance measurement, staff members could determine the sigma levels as upper and lower limits.*
	Create Control Charts and monitor the improved process	*Perfection*	*Control charts*		*Control charts and process data*	*Staff members could use control charts to monitor and control the existing process to maintain previous improvements.*
	Correct the improved process (if out of control)			*(Model the modification in simulation)*	*(Modified simulation models)*	*If the process is out of control, adjustment should be made. (Building a simulation model may again help.)*
	Document efforts and outcomes			*Document the results*	*Process data and results*	*Any changes and improvements should be documented and be transparent to all staff members.*
	Be transparent to all staff members		*Visual management*		*Controlled process*	*Regular meetings and visualized tools are important.*

Steps in italics are not part of this thesis, will likely be done by hospital staff – they are included in order to show a complete framework that combines the three methods

Table 13: A general framework for combining Six Sigma, lean and simulation

DMAIC	STEP	LEAN PRINCIPLE	TOOLS that may be helpful	SIMULATION STEP	OUTCOME	NOTE
Define	Describe problem symptoms	Value	Meetings, Observations	Understand the system	Problems/chances of improvement	It is usually a starting point of an improvement project that recognizing problems/chances of improvement in a process.
	Define the process to be improved (project scope)		Meetings, Observations	Understand the system	Project scope, Overall picture of the process	It is necessary to decide the project scope and its boundaries.
	Collect/review relevant historical data		Microsoft Excel	Understand the system	Process characteristics	By reviewing the historical data, we can learn how the process performed before. It helps to understand the process.
	Define performance measurements	Value	Meetings, Interviews, QFD	Be clear about the goals	Performance measurements	It requires focusing on the "voice of customer" and the standpoint of an entire process when defining performance measurements.
	Create a project team		Meetings, Interviews	Run some pre-built models	Project team leader and members with clear knowledge of lean and Six Sigma	Some pre-built simulation models can serve as a tool to explore the strategies of lean and Six Sigma and get staff involved and support the project (Robinson et al., 2012).
	Create a project charter	Value	Meetings, Interviews	Be clear about the goals	Project statement, scope, goals (e.g. Six Sigma level), performance measures,	The process problems, scope, goals, management commitment, involved staff, agenda need to be settled and committed to all the team members.

DMAIC	STEP	LEAN PRINCIPLE	TOOLS that may be helpful	SIMULATION STEP	OUTCOME	NOTE
Measure	Create a detailed process map	Value stream map (VSM)	Observations and interviews	Formulate the model representation	Detailed system/process maps	A detailed process map helps to better understand the process/system, identify variables and facilitate data collection later.
	Identify variables and expressions		Meetings, Interviews		Variables and expressions	Variables are the factors that we can change or control within the process/system which will influence the CTQs.
	Define sample size and data collection plan		Meetings, Observations, Microsoft Excel		Data collection plan	A sample size should be decided depended on the size of population and statistical concern. Reviewing the historical data may be helpful.
	Collect relevant data and clean the data		Observations, Interviews, Microsoft Excel	Time study and observations	Cleaned data	Communication with staff members is necessary. Variables identified before should be paid attention in the data collection. Relevant time and occurred frequency should be recorded.
	Build value stream maps and measure different activities	VSM	Microsoft Excel, PowerPoint, Arena, Takt Time		Value stream maps	Value stream maps can be built in PPT or Arena. Three categories of activities are classified and measured (value added, non-value added but necessary, and non-value added activities). Takt time may be useful for Flow analysis later.
	Validate the value stream map	VSM	Microsoft Excel		Validated value stream maps	The value stream map should be validated by comparing with the historical data.

DMAIC	STEP	LEAN PRINCIPLE	TOOLS that may be helpful	SIMULATION STEP	OUTCOME	NOTE
Measure (cont.)	Calculate the capability of the process				Process current capability	The process capability can be transferred to related Six Sigma level, which can become one of the goals to be improved.
	Translate the VSM into modeling software		Arena	Translate into modeling software	Value stream maps in Simulation	Complete and detailed value stream maps in simulation represents the current stage of the process (base model).
Analyze	Analyze historical and observational data		Microsoft Excel		Process pattern and tendency	This could be used to validate the simulation model and facilitate the Improve stage later.
	Determine causes of problems and gather data on the causes (quantify the causes)	Flow	Observation, Meetings, Microsoft Excel & PowerPoint, Pareto Chart, 5 WHY, Cause & effect diagram, Spaghetti Diagram		Problem causes and their relevant data (e.g. time and frequency)	Observations, meetings and 5 WHY are used to generate potential causes of the problem. The Cause-Effect Diagram classifies the causes of problem, and a Pareto Chart shows the time and frequency of causes. The Spaghetti Diagram shows the movement (travel pattern) of the people involved in the process. These analytical results will facilitate developing potential improvements later in the Improve stage.
	Determine the best fit distributions of input data		Input analyzer, Best fit	Input the data distributions into the model	Statistical data, Model of current stage	Data may need to be prescreened before fitting. Different distribution fitter can be used to find the best fit distributions of the data.

DMAIC	STEP	LEAN PRINCIPLE	TOOLS that may be helpful	SIMULATION STEP	OUTCOME	NOTE
Analyze (cont.)	Verify and validate the simulation model		Arena, Microsoft Excel	Verification and validation	A representative model of the current stage	Methods of simulation model verification and validation will be applied (e.g. review model code and compare with historical data).
	Document the simulation outputs		Arena, Microsoft Excel	Run the model	Base line data	Waiting time, resource utilization or other performance measurements can be generated quickly by running the simulation models.
Improve	Develop potential suggestions	Flow Pull	Meetings, Standard work, 5S, Batch size reduction, Visual management		Potential suggestions	Suggestions are developed based on the causes of problem.
	Model different suggestions in simulation		Arena	Design the experiments and run the different suggestions	Potential outcomes	It could build different simulation models to get results of different suggestions. It is not required that all the suggestions should be verified in the simulation model. The simulation models predict potential outcomes of implementing the suggestions.
	Evaluate different outcomes		Output analyzer, ANOVA test/SPSS	Analyze the results Get insight	Statistically supportive suggestions	The Simulation outcomes and statistical analysis support and explain the potential consequences of implementation.

DMAIC	STEP	LEAN PRINCIPLE	TOOLS that may be helpful	SIMULATION STEP	OUTCOME	NOTE
Improve (cont.)	Implementation (by hospital staff)		Microsoft Excel		Implementation plans	Analyze historical data may facilitate the implementation. May carry out some trial tests first and then transfer to regular operation
Control	Determine the process control limits (sigma levels)	Perfection	Meetings		Control limits	By calculating the mean and standard deviation of a performance measurement, staff members could determine the sigma levels as upper and lower limits.
	Create Control Charts and monitor the improved process	Perfection	Control charts		Control charts and process data	Staff members could use control charts to monitor and control the existing process to maintain previous improvements.
	Modify the improved process (if out of control)			(Model the modification in simulation)	(Modified simulation models)	If the process is out of control, adjustment should be made. (Building a simulation model may again help.)
	Document efforts and outcomes			Document the results	Process data and results	Any changes and improvements should be documented and be transparent to all staff members.
	Be transparent to all staff members		Visual management		Controlled process	Regular meetings and visualized tools are important.

6. Conclusion

The phlebotomy process affects various medical outcomes, but it has been studied rarely in previous literature. Moreover, lean, Six Sigma and simulation have rarely been combined and used in a single process improvement study. This study aimed to understand and improve the phlebotomy process as well as provide an integrated framework by using these three methodologies. Their usage in the phlebotomy process not only demonstrated their complementary roles in process improvement projects, but also provided the phlebotomy process in particular with significant suggestions and insights as a result of using them together.

Observations and interviews were two primary tools used to understand and measure the process. With the help of value stream maps, we were able to identify the delays (i.e., waste) within the process. The relevant data collected from observation were analyzed with cause-effect diagrams and Pareto charts. In order to address the most frequent causes of delay, we came up with 11 suggestions to reduce the process wastes and variability. Simulation modeling was applied to demonstrate the impact of most of the suggestions.

The simulation models and statistical results showed that all suggestions can result in a significant improvement in the processes. The UC process will achieve a 7.75-minute reduction in flow time if the hospital maintains the float nurse in the UC with blood collection as the first priority; the ER process will save 6.73 minutes if the nurse collects the blood before other examinations and sends it to the lab right after. If these suggestions are not feasible, second and third ideas are recommended, discussed above at the end of section 4.4.2.

For other hospitals, the phlebotomy process would not be exactly the same and thus precise suggestions are not possible. However, some general ideas can be generated from this work. If delays in ED phlebotomy are a problem, it is suggested that a nurse or MLA be assigned to carry out the phlebotomy process only, not doing any other tasks, to prevent interruptions or delays. Secondly, a nurse or MLA could draw the blood first,

before carrying out other examinations, because a blood test usually takes a longer time to process than other examinations (e.g., X-ray). This is a scheduling or order of procedure decision for individual patients. A third option is that the hospital could assign a "special duty" nurse or MLA, whose first priority is to draw blood, and who can only do other work when no blood draws are required.

In addition, a structured framework was generated to summarize how lean, Six Sigma and simulation were combined to analyze the St Catharines phlebotomy process. It was recognized that this framework also has the capability for process improvement in other health care processes that experience high variability and complexity. Therefore, a general framework was created to guide future process improvement efforts in health care.

7. Limitations and Future Study

Every process has potential to experience different types of problems. By combining Six Sigma, lean and simulation methodologies, a comprehensive methodology has been developed that can be used to evaluate and analyze multiple performance measures at the same time. For example, error rate and waiting time are two popular performance measurements in health care. Error rate is directly related to patient safety and waiting time has been proven to affect patient satisfaction. This thesis only focuses on the flow time of a process; we do not account for additional performance measures. The largest opportunity for future study based on this thesis is to investigate a wider range of performance measures with this methodology.

In addition to performance measurement, this study is restricted by its small sample size. Despite collecting data for over 100 hours, only about 100 instances of phlebotomy were observed. A larger sample size could give more precise information for modeling purposes, which could increase the quality of results.

Having just one observer who didn't even have access to all data points (e.g., the phlebotomy order time, as explained earlier) is another limitation. More attention could be paid to the data collection in the future in order to more accurately establish the actual times.

Another limitation of this thesis is that we could not get entirely accurate historical data from the hospital, due to the limitation of the hospital IT system. The blood test order frequency data that the hospital provided included the RAZ patients which were not within this thesis' scope. Some assumptions were needed to separate out these patients and the information needed. Thus, it should be possible to obtain more precise information in the future.

Finally, it is apparent that this study only focuses on the phlebotomy process, and does not account for other hospital processes. Some suggestions proposed may have negative effects on other process, but we are not aware of what those might be. Thus, a more

comprehensive future study could consider analyzing more of the hospital system and the interrelationships between processes.

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Appendix

Appendix A: UC Tukey Test- Multiple Comparisons

Dependent Variable: Flow Time						
Case	Case	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
AD	C	-3.16	.07	0.00	-3.36	-2.97
	D	-0.07	.07	0.92	-0.26	0.13
	E	0.23	.07	0.01	0.03	0.42
	O	-7.53	.07	0.00	-7.72	-7.33
	P	15.88	.07	0.00	15.69	16.07
C	AD	3.16	.07	0.00	2.97	3.36
	D	3.10	.07	0.00	2.90	3.29
	E	3.39	.07	0.00	3.20	3.59
	O	-4.37	.07	0.00	-4.56	-4.17
	P	19.04	.07	0.00	18.85	19.24
D	AD	0.07	.07	0.92	-0.13	0.26
	C	-3.10	.07	0.00	-3.29	-2.90
	E	0.30	.07	0.00	0.10	0.49
	O	-7.46	.07	0.00	-7.66	-7.27
	P	15.95	.07	0.00	15.75	16.14
E	AD	-0.23	.07	0.01	-0.42	-0.03
	C	-3.39	.07	0.00	-3.59	-3.20
	D	-0.30	.07	0.00	-0.49	-0.10
	O	-7.76	.07	0.00	-7.95	-7.56
	P	15.65	.07	0.00	15.46	15.85
O	AD	7.53	.07	0.00	7.33	7.72
	C	4.37	.07	0.00	4.17	4.56
	D	7.46	.07	0.00	7.27	7.66
	E	7.76	.07	0.00	7.56	7.95
	P	23.41	.07	0.00	23.21	23.60
P	AD	15.88	.07	0.00	16.07	15.69
	C	19.04	.07	0.00	19.24	18.85
	D	15.95	.07	0.00	16.14	15.75
	E	15.65	.07	0.00	15.85	15.46
	O	23.41	.07	0.00	23.60	23.21
Based on observed means.						
The error term is Mean Square(Error) = 6.989.						
*. The mean difference is significant at the .05 level.						

Appendix B: UC Pairwise Comparisons

Dependent Variable: Flow Time							
Case	Demand Level	Demand Level	Mean Difference	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
AD	0	10	-1.02	0.12	0.00	-1.25	-0.79
		20	-2.08	0.12	0.00	-2.31	-1.85
	10	0	1.02	0.12	0.00	0.79	1.25
		20	-1.06	0.12	0.00	-1.29	-0.83
	20	0	2.08	0.12	0.00	1.85	2.31
		10	1.06	0.12	0.00	0.83	1.29
C	0	10	-0.10	0.12	0.39	-0.33	0.13
		20	-0.20	0.12	0.10	-0.43	0.04
	10	0	0.10	0.12	0.39	-0.13	0.33
		20	-0.10	0.12	0.42	-0.33	0.14
	20	0	0.20	0.12	0.10	-0.04	0.43
		10	0.10	0.12	0.42	-0.14	0.33
D	0	10	-0.91	0.12	0.00	-1.14	-0.68
		20	-2.06	0.12	0.00	-2.29	-1.83
	10	0	0.91	0.12	0.00	0.68	1.14
		20	-1.15	0.12	0.00	-1.38	-0.92
	20	0	2.06	0.12	0.00	1.83	2.29
		10	1.15	0.12	0.00	0.92	1.38
E	0	10	-0.39	0.12	0.00	-0.62	-0.16
		20	-0.77	0.12	0.00	-1.00	-0.54
	10	0	0.39	0.12	0.00	0.16	0.62
		20	-0.38	0.12	0.00	-0.61	-0.15
	20	0	0.77	0.12	0.00	0.54	1.00
		10	0.38	0.12	0.00	0.15	0.61
O	0	10	-0.05	0.12	0.66	-0.28	0.18
		20	-0.15	0.12	0.21	-0.38	0.08
	10	0	0.05	0.12	0.66	-0.18	0.28
		20	-0.10	0.12	0.42	-0.33	0.14
	20	0	0.15	0.12	0.21	-0.08	0.38
		10	0.10	0.12	0.42	-0.14	0.33
P	0	10	-0.09	0.12	0.44	-0.32	0.14
		20	-0.10	0.12	0.38	-0.34	0.13
	10	0	0.09	0.12	0.44	-0.14	0.32
		20	-0.01	0.12	0.91	-0.25	0.22
	20	0	0.10	0.12	0.38	-0.13	0.34
		10	0.01	0.12	0.91	-0.22	0.25
Based on estimated marginal means							
*. The mean difference is significant at the .05 level.							
b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).							

Appendix C: ER Tukey Test- Multiple Comparisons

Dependent Variable: Flow Time						
Case	Case	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
A	AB	3.04	0.04	0.00	2.90	3.19
	AD	6.73	0.04	0.00	6.58	6.87
	AF	3.26	0.04	0.00	3.12	3.41
	B	-0.73	0.04	0.00	-0.88	-0.58
	D	3.15	0.04	0.00	3.00	3.30
	F	-0.10	0.04	0.46	-0.25	0.04
	G	-1.78	0.04	0.00	-1.93	-1.64
	O	-3.47	0.04	0.00	-3.62	-3.33
	P	14.99	0.04	0.00	14.84	15.13
AB	A	-3.04	0.04	0.00	-3.19	-2.90
	AD	3.68	0.04	0.00	3.54	3.83
	AF	0.22	0.04	0.00	0.07	0.37
	B	-3.77	0.04	0.00	-3.92	-3.63
	D	0.11	0.04	0.37	-0.04	0.25
	F	-3.14	0.04	0.00	-3.29	-3.00
	G	-4.82	0.04	0.00	-4.97	-4.68
	O	-6.52	0.04	0.00	-6.66	-6.37
	P	11.95	0.04	0.00	11.80	12.09
AD	A	-6.73	0.04	0.00	-6.87	-6.58
	AB	-3.68	0.04	0.00	-3.83	-3.54
	AF	-3.46	0.04	0.00	-3.61	-3.32
	B	-7.46	0.04	0.00	-7.60	-7.31
	D	-3.58	0.04	0.00	-3.72	-3.43
	F	-6.83	0.04	0.00	-6.97	-6.68
	G	-8.51	0.04	0.00	-8.65	-8.36
	O	10.20	0.04	0.00	10.35	10.05
	P	8.26	0.04	0.00	8.12	8.41
AF	A	-3.26	0.04	0.00	-3.41	-3.12
	AB	-0.22	0.04	0.00	-0.37	-0.07
	AD	3.46	0.04	0.00	3.32	3.61
	B	-3.99	0.04	0.00	-4.14	-3.85
	D	-0.11	0.04	0.30	-0.26	0.03
	F	-3.36	0.04	0.00	-3.51	-3.22
	G	-5.04	0.04	0.00	-5.19	-4.90
	O	-6.74	0.04	0.00	-6.88	-6.59
	P	11.73	0.04	0.00	11.58	11.87
B	A	0.73	0.04	0.00	0.58	0.88
	AB	3.77	0.04	0.00	3.63	3.92
	AD	7.46	0.04	0.00	7.31	7.60
	AF	3.99	0.04	0.00	3.85	4.14
	D	3.88	0.04	0.00	3.73	4.03
	F	0.63	0.04	0.00	0.48	0.77
	G	-1.05	0.04	0.00	-1.20	-0.91
	O	-2.74	0.04	0.00	-2.89	-2.60
	P	15.72	0.04	0.00	15.57	15.86
D	A	-3.15	0.04	0.00	-3.30	-3.00

	AB	-0.11	0.04	0.37	-0.25	0.04
	AD	3.58	0.04	0.00	3.43	3.72
	AF	0.11	0.04	0.30	-0.03	0.26
	B	-3.88	0.04	0.00	-4.03	-3.73
	F	-3.25	0.04	0.00	-3.40	-3.11
	G	-4.93	0.04	0.00	-5.08	-4.79
	O	-6.62	0.04	0.00	-6.77	-6.48
	P	11.84	0.04	0.00	11.69	11.98
F	A	0.10	0.04	0.46	-0.04	0.25
	AB	3.14	0.04	0.00	3.00	3.29
	AD	6.83	0.04	0.00	6.68	6.97
	AF	3.36	0.04	0.00	3.22	3.51
	B	-0.63	0.04	0.00	-0.77	-0.48
	D	3.25	0.04	0.00	3.11	3.40
	G	-1.68	0.04	0.00	-1.83	-1.53
	O	-3.37	0.04	0.00	-3.52	-3.23
	P	15.09	0.04	0.00	14.94	15.24
G	A	1.78	0.04	0.00	1.64	1.93
	AB	4.82	0.04	0.00	4.68	4.97
	AD	8.51	0.04	0.00	8.36	8.65
	AF	5.04	0.04	0.00	4.90	5.19
	B	1.05	0.04	0.00	0.91	1.20
	D	4.93	0.04	0.00	4.79	5.08
	F	1.68	0.04	0.00	1.53	1.83
	O	-1.69	0.04	0.00	-1.84	-1.55
	P	16.77	0.04	0.00	16.62	16.92
O	A	3.47	0.04	0.00	3.33	3.62
	AB	6.52	0.04	0.00	6.37	6.66
	AD	10.20	0.04	0.00	10.05	10.35
	AF	6.74	0.04	0.00	6.59	6.88
	B	2.74	0.04	0.00	2.60	2.89
	D	6.62	0.04	0.00	6.48	6.77
	F	3.37	0.04	0.00	3.23	3.52
	G	1.69	0.04	0.00	1.55	1.84
	P	18.46	0.04	0.00	18.32	18.61
P	A	14.99	0.04	0.00	15.13	14.84
	AB	11.95	0.04	0.00	12.09	11.80
	AD	-8.26	0.04	0.00	-8.41	-8.12
	AF	11.73	0.04	0.00	11.87	11.58
	B	15.72	0.04	0.00	15.86	15.57
	D	11.84	0.04	0.00	11.98	11.69
	F	15.09	0.04	0.00	15.24	14.94
	G	16.77	0.04	0.00	16.92	16.62
	O	18.46	0.04	0.00	18.61	18.32

Based on observed means.
The error term is Mean Square(Error) = 3.179.

*. The mean difference is significant at the .05 level.

Appendix D: ER Pairwise Comparisons

Dependent Variable: Flow Time							
Case	Demand Level	Demand Level	Mean Difference	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
A	0	10	-0.03	0.08	0.74	-0.18	0.13
		20	-0.04	0.08	0.62	-0.20	0.12
	10	0	0.03	0.08	0.74	-0.13	0.18
		20	-0.01	0.08	0.87	-0.17	0.14
	20	0	0.04	0.08	0.62	-0.12	0.20
		10	0.01	0.08	0.87	-0.14	0.17
AB	0	10	0.00	0.08	0.97	-0.16	0.15
		20	-0.01	0.08	0.95	-0.16	0.15
	10	0	0.00	0.08	0.97	-0.15	0.16
		20	0.00	0.08	0.98	-0.16	0.15
	20	0	0.01	0.08	0.95	-0.15	0.16
		10	0.00	0.08	0.98	-0.15	0.16
AD	0	10	-0.86	0.08	0.00	-1.02	-0.71
		20	-1.89	0.08	0.00	-2.05	-1.74
	10	0	0.86	0.08	0.00	0.71	1.02
		20	-1.03	0.08	0.00	-1.19	-0.87
	20	0	1.89	0.08	0.00	1.74	2.05
		10	1.03	0.08	0.00	0.87	1.19
AF	0	10	0.02	0.08	0.77	-0.13	0.18
		20	-0.05	0.08	0.51	-0.21	0.10
	10	0	-0.02	0.08	0.77	-0.18	0.13
		20	-0.08	0.08	0.34	-0.23	0.08
	20	0	0.05	0.08	0.51	-0.10	0.21
		10	0.08	0.08	0.34	-0.08	0.23
B	0	10	-0.05	0.08	0.55	-0.20	0.11
		20	0.01	0.08	0.89	-0.15	0.17
	10	0	0.05	0.08	0.55	-0.11	0.20
		20	0.06	0.08	0.46	-0.10	0.22
	20	0	-0.01	0.08	0.89	-0.17	0.15
		10	-0.06	0.08	0.46	-0.22	0.10
D	0	10	-1.00	0.08	0.00	-1.16	-0.84
		20	-2.00	0.08	0.00	-2.16	-1.85
	10	0	1.00	0.08	0.00	0.84	1.16
		20	-1.00	0.08	0.00	-1.16	-0.85
	20	0	2.00	0.08	0.00	1.85	2.16
		10	1.00	0.08	0.00	0.85	1.16
F	0	10	-0.05	0.08	0.52	-0.21	0.11
		20	0.02	0.08	0.80	-0.14	0.18
	10	0	0.05	0.08	0.52	-0.11	0.21
		20	0.07	0.08	0.37	-0.08	0.23
	20	0	-0.02	0.08	0.80	-0.18	0.14
		10	-0.07	0.08	0.37	-0.23	0.08
G	0	10	0.00	0.08	0.96	-0.15	0.16
		20	-0.02	0.08	0.79	-0.18	0.14
	10	0	0.00	0.08	0.96	-0.16	0.15

		20	-0.03	0.08	0.75	-0.18	0.13
	20	0	0.02	0.08	0.79	-0.14	0.18
		10	0.03	0.08	0.75	-0.13	0.18
O	0	10	-0.14	0.08	0.07	-0.30	0.01
		20	-0.11	0.08	0.19	-0.26	0.05
	10	0	0.14	0.08	0.07	-0.01	0.30
		20	0.04	0.08	0.62	-0.12	0.20
	20	0	0.11	0.08	0.19	-0.05	0.26
		10	-0.04	0.08	0.62	-0.20	0.12
P	0	10	0.05	0.08	0.54	-0.11	0.21
		20	0.02	0.08	0.85	-0.14	0.17
	10	0	-0.05	0.08	0.54	-0.21	0.11
		20	-0.03	0.08	0.67	-0.19	0.12
	20	0	-0.02	0.08	0.85	-0.17	0.14
		10	0.03	0.08	0.67	-0.12	0.19

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).